Groundwater flow systems in the northern coastal lowlands of West- and Central Java, Indonesia

Kloosterman, F.H.

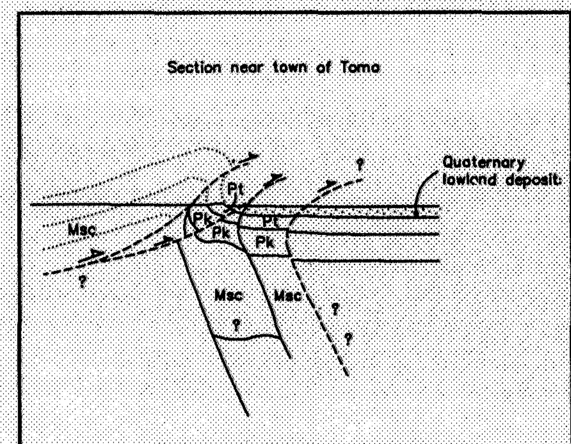
1989

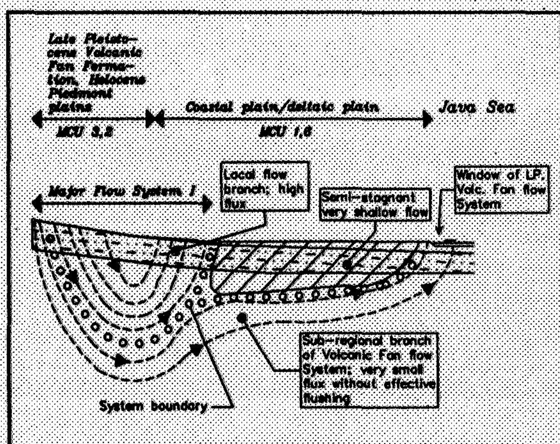
FREE UNIVERSITY, AMSTERDAM

GROUNDWATER FLOW SYSTEMS IN THE NORTHERN COASTAL LOWLANDS OF WEST- AND CENTRAL JAVA, INDONESIA

An Earth-Scientific Approach

by
F.H. Kloosterman





VRIJE UNIVERSITEIT TE AMSTERDAM

GROUNDWATER FLOW SYSTEMS IN THE NORTHERN COASTAL LOWLANDS OF WEST- AND CENTRAL JAVA, INDONESIA

An Earth-Scientific Approach

ACADEMISCH PROEFSCHRIFT
ter verkrijging van de graad van doctor aan
de Vrije Universiteit te Amsterdam,
op gezag van de rector magnificus
prof. dr. C. Datema,
hoogleraar aan de faculteit der letteren,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der aardwetenschappen
op donderdag 2 november 1989 te 13.30 uur
in het hoofdgebouw van de universiteit, De Boelelaan 1105

door
Fred Henri Kloosterman
geboren te Palembang (Indonesië)

Kanisius, Yogyakarta
1989

Promotor	prof.dr. G.B. Engelen
Referenten	prof.dr. H. Th. Verstappen
	prof.ir. A. Volker

'Ask simple questions, because the answers to complicated questions will be too complicated to test and, even worse, too fascinating to give up'
(Alfred W. Crosby, 1986)

To Emmy, Roald and my Parents.

CONTENTS

Acknowledgements 1

Summary 3

Samenvatting 8

I. INTRODUCTION 14
- 1.1 General aspects of coastal lowlands in the humid tropics 14
- 1.2 Geography of the area of investigation 16
- 1.3 Problems in the northern coastal lowlands of Java 21
  - 1.3.1 Aspects of Human Inhabitation 21
  - 1.3.2 Water supply and salinization 25
- 1.4 Previous research in the northern coastal lowlands of Java 26
- 1.5 Organizational framework 29

II. METHODOLOGY 31
- 2.1 Earth and water systems approach 31
  - 2.1.1 Introduction 31
  - 2.1.2 System concept in hydrology and historical development 31
  - 2.1.3 Hierarchy and mutual relations in water and earth systems 33
- 2.2 System approach in the present study 35
  - 2.2.1 General system framework 35
  - 2.2.2 Aspects of time and scale 36
- 2.3 Scientific framework 38
- 2.4 Outline and order of chapters 40

III. THE TERTIARY EVOLUTION OF JAVA IN A FRAMEWORK OF REGIONAL PLATE TECTONICS 42
- 3.1 Present-day regional plate tectonics setting 42
  - 3.1.1 Introduction 42
  - 3.1.2 Main plate tectonic elements 43
  - 3.1.3 Island-arc volcanism 45
- 3.2 Tertiary evolution of the Java island arc 46
  - 3.2.1 Paleogene fossil melanges 46
  - 3.2.2 Major plate events in the Indian Ocean 48
  - 3.2.3 Synopsis of geological developments in West- and Central Java during the Tertiary 55
  - 3.2.4 Cycles and patterns in the geological development of Java 59
- 3.3 Miocene and Pliocene formations in the kabupatens Tegal and Brebes 61
  - 3.3.1 Introduction 61

3.3.2 Pemali Formation (Lower-Middle Miocene) 61
3.3.3 Rambatan and Lawak Formations (Middle Miocene) 62
3.3.4 Halang Formation (Middle-Upper Miocene) 63
3.3.5 Kumbang Formation (Upper Miocene-Lower Pliocene) 65
3.3.6 Tapak Formation (Lower-Middle Pliocene) 65
3.3.7 Kalibiuk Formation (Middle Pliocene) 65
3.3.8 Kaliglagah/Cijulang Formation (Upper Pliocene) 66
3.3.9 Concluding remarks on the Mio-Pliocene formations in Tegal and Brebes 67

IV. THE PLEISTOCENE EMERGENCE OF JAVA AND MAJOR GEOLOGIC EVENTS 68
4.1 Introduction 68
4.2 Pleistocene geological evolution of North Java 68
4.2.1 Introduction 68
4.2.2 Major Pleistocene stages in North Java 69
4.2.3 The stratigraphic significance of some Pleistocene rock sections 73
4.2.4 General patterns of Pleistocene tectonics 79
4.2.5 Tectonics in the hinterlands south of the northern coastal lowlands 85
4.2.6 Summary of the major geologic events during the Pleistocene 93
4.3 Climatic conditions during the Pleistocene 94
4.3.1 Introduction 94
4.3.2 Quaternary climatic conditions and coastal lowland development 98
4.3.3 Geological evidence in the study area for Pleistocene climatic fluctuations 100
4.3.3.1 Introduction 100
4.3.3.2 Extensive surfaces of low relief 101
4.3.3.3 The Significance of Volcanogenic Gravels in the Hinterland Catchments 104
4.3.3.4 The Prupuk reef limestones 106
4.3.3.5 The low-relief surface on the Gintung Formation in Cirebon 109
4.3.3.6 The Late Pleistocene Volcanic Fan Deposits in the Coastal Lowlands of West Java 109
4.4 Discussion and Synthesis 110

V. REGIONAL PLEISTOCENE STRATIFICATION IN THE COASTAL LOWLANDS 114
5.1 Introduction 114
5.2 Sedimentation in the Quaternary basins 115
5.3 Depth distributions of water wells in the coastal lowlands 119
5.3.1 Introduction 119
5.3.2 Collected water well data 120

5.3.3 Statistical analyses of tube wells depths 122
5.4 Results and discussion 140

VI. EXTERNAL FEATURES OF THE COASTAL LOWLANDS 145
6.1 Introduction 145
6.2 Analysis of slope vectors in the coastal lowlands 145
6.2.1 Available map data and statistical procedures 145
6.2.2 Results of the slope vector analysis 147
6.2.3 Discussion 155
6.2.4 Morphological zoning of the coastal lowlands 156
6.2.5 Hydrogeological implications of sediments found in the four morphological zones 160

VII. GROUNDWATER SYSTEMS IN THE COASTAL LOWLANDS 165
7.1 Introduction 165
7.2 General hydrological background characteristics 165
7.3 General field methodology, data collection and processing 168
7.4 Kabupaten Karawang 169
7.4.1 General physical setting 169
7.4.2 General groundwater setting 171
7.4.3 Hydrochemical cross sections through kabupaten Karawang 173
7.4.4 Conclusions on the groundwater hydrochemistry in kabupaten Karawang 185
7.5 Kabupaten Subang 185
7.5.1 General physical setting 185
7.5.2 General groundwater setting 187
7.5.3 Stratigraphic investigations on two deep wells south of the town Pamanukan 189
7.5.4 Hydrochemical cross sections through kabupaten Subang 192
7.5.5 Conclusions on the groundwater hydrochemistry in kabupaten Subang 200
7.6 Kabupaten Indramayu 201
7.6.1 General physical setting 201
7.6.2 General groundwater setting 204
7.6.3 Hydrochemical cross sections through kabupaten Indramayu 206
7.6.4 Shallow groundwaters in the upper deltaic plain of the Cimanuk river 211
7.7 Kabupaten Cirebon 221
7.7.1 General physical setting 221
7.7.2 General groundwater setting 224
7.7.3 Hydrochemical cross sections through kabupaten Cirebon 226
7.7.4 Conclusions on the hydrogeology in kabupaten Cirebon 232

7.8 Kabupatens Brebes and Tegal (Central Java) 233
7.8.1 Introduction 233
7.8.2 General physical setting 233
7.8.3 Major tectonic structures 237
7.8.4 General groundwater setting 239
7.8.5 Hydrochemical cross sections through kabupatens Brebes and Tegal 241
7.8.6 Highly mineralized shallow groundwaters in southern parts of the coastal lowlands 248
7.8.7 Conclusions on groundwater hydrochemistry in kabupatens Brebes and Tegal 251
7.9 Remaining aspects of groundwaters in the northern coastal lowlands 252
7.9.1 Artesian flow 252

VIII. SYNTHESIS 262

List of Figures 272

List of Tables 274

Appendix I 277

Appendix II 279

References 289

ACKNOWLEDGEMENTS

At the completion of this thesis I feel particularly indebted to Prof. Dr. G.B. Engelen, Professor of Hydrogeology and Geographical Hydrology at the Institute of Earth Sciences, Free University, Amsterdam (FUA), who promoted this study. Sincere appreciation is hereby expressed for the way he stimulated me and convinced me to expand the investigation framework from the coastal lowlands proper to the level of Java plate tectonics and the geological developments from Tertiary times onwards. To him goes the credit for the idea, developed during a number of fieldtrips together with the author, that the Quaternary basin history is reflected in morphological and pedogenetic features in the hinterland and that clues of an earth scientific nature, which may help to unravel the intricate groundwater hydrology in the lowlands, should thus be searched for in the fringing areas.

Special thanks are due to Prof. Dr. I. Simmers, also from the Institute of Earth Sciences, Free University, who critically read the manuscript and edited the English text. Gratefully acknowledged is the prompt 'backstop' support he always provided the author from Amsterdam.

The author is indebted to Prof. Dr. W. Roeleveld for his critical comments during fieldtrips with the author and the nightly discussions in Tegal on the 'riddle' of clay pebbles in channel lag deposits. He is especially thanked for his assistance in arranging for the radiocarbon dating of wood samples at the Isotope Physics Laboratory of the University of Groningen, and his unabated efforts to find such an expert as Dr. C. Beets, retired paleontologist of the Shell Oil Company, for Mollusca shell determinations in beach rocks. Thanks are due to Dr. Beets for his written report on a key exposure in Tegal.

I would like to thank Prof. Dr. H.Th. Verstappen, Head of the Geomorphology and Geography department of the International Institute for Aerial Survey and Earth Sciences (ITC), for his remarks and suggestions on maps and drawings during visits to Yogyakarta.

Dr. Ir. E. Seyhan is thanked for commenting on statistical analyses in the Chapters V and VI.

Special thanks are due to Dr. Karmono Mangunsukardjo, Dean of the Faculty of Geography, Gadjah Mada University, and Dr. Sutikno and Drs. Soenarso Simoen, counterparts of the author in the NUFFIC sponsored ESP project, who were always ready for assistance.

Many people at the Faculty of Geography have helped the author, in particular the drivers and technicians who faithfully accompanied him on fieldtrips. The Indonesian students Achmad Zaini Ichwan, Djoko Kuntjoro, Endro Sulistiyanto, Tonny Hasundungan, Haris Priyo Widodo, FX Pratomo, Sutopo Setiawan and Adi Winanto, and the Dutch FUA students M.A. Gischler, M.A. Wijckerheld Bisdom, P. Dijckmeester and H. Kamphuis are thanked for collecting valuable field information.

Special thanks are due to Dr. F. Hehuwat of the Institute LIPI/LGPN, Bandung for his constructive support during the period when surveying was executed in cooperation with

LIPI staff. Gratitude must be expressed to the staff of the chemical laboratory for their assistance during field surveys and chemical analyses of the water samples

Finally, the NUFFIC sponsored 'Earth Sciences Project' phases 3 and 4 must be acknowledged for making available project facilities.

SUMMARY

This study is concerned with groundwater systems in the coastal lowlands of North Java, Indonesia. More precisely, the area comprises the kabupatens (Indonesian administrative subdivision of a province) Karawang, Subang, Indramayu and Cirebon in the province of West Java and the kabupatens Brebes and Tegal in the province of Central Java. The coastal lowlands geologically comprise an argillaceous Quaternary sediment pile presumably 200-300 m thick which continues far under the shallow epicontinental Java Sea. Typical depositional environments include shallow marine, near-shore, deltaic, fluvial flood plain and alluvial-volcanic fans. Most of the sediments are derived from erosion of folded Tertiary argillaceous rocks and Quaternary volcanics in the hilly hinterlands. Groundwater exploitation is hampered by poor permeabilities and widely varying water qualities both in depth and spatially. Strongly mineralized groundwaters are present in terrestrial sediments tens of kilometres from the present-day coast. The general hydrogeological framework deviates strongly from classical concepts of coastal aquifers with sharp fresh-salt water interfaces.

In order to unravel the complicated groundwater hydrology of these coastal lowlands, the approach taken has been to trace geological developments on Java from the framework of large time and space scales down to the level of present lowland sedimentation. Rationale behind this approach of hierarchical reductionism is that the hydrogeological complexity of the lowlands should be viewed in the wider context of a geological and tectonic framework. Much effort has been spent in studying geological, morphological and pedogenetic features in the hilly Tertiary hinterlands, shedding light on the depositional history and conditions in Quaternary basins of the lowlands.

Chapter I reviews the general physical aspects of extensive coastal lowlands in the humid tropics and the accompanying problems of dense inhabitation by settlers practising wet-rice cultivation. From a historical and cultural point of view, these coastal lowlands in the north of Java and the broad alluvial valleys found in the central depression, have played crucial roles in affording southerly waves of human migration from mainland Asia.

The study methodology and system concept are elaborated in Chapter II. It is shown that the geological framework in which processes have taken place, relevant to the studied area, should be expanded to the scale of a consuming plate margin and should date back to the beginning of the Tertiary period. The geological developments are traced by following a tree structure of scale and time. With each step the branches are descended and objects are being studied at reduced scales in time and space. Important is the aspect of inheritance, implying that objects at a certain rank in the hierarchy of time and space may have inherited characteristics from objects at higher levels. Special attention is paid to the longstanding problem of Quaternary climatic fluctuations on Java, the surmised remnants of polygenetic landforms and effects of the fluctuations on sedimentary basin filling.

The Tertiary evolution of Java in the framework of an oceanic plate subduction model is outlined in Chapter III and a description is given of the major system elements. Late Cretaceous to Early Tertiary melange exposed in Bayat and Karangsambung, Central Java is described in detail. During the formation of this melange wedge the volcanic arc was positioned along the southern margin of the present-day Java Sea. A remarkably quiet time span, also noted by other workers on the tectonics of the Indonesian region, is recorded in silicaclastic rocks and reef limestones of Eocene and Oligocene age. In the present study it is postulated that this remarkably quiescent interval, devoid of magmatic activity in the belt

of present-day Java, is attributable to global reorganizations of mega-plate boundaries, also affecting spreading centres in the Indian ocean. From 80 to 54 Ma ago an oceanic spreading centre at perhaps not more than 3,000 km south of Java was responsible for the formation of the melange wedge exposed in Bayat and Karangsambung and a volcanic line in the present-day Java Sea. At 54 Ma a complete reorganization of spreading centres occurred in the Indian Ocean with a jump of the ridge from between Eurasia and Australia to between Australia and Antarctica. This is thought to have caused a significant decrease in subduction rates beneath Java. Subduction may have been reestablished at the 35 Ma event when drastic changes of the Pacific oceanic plate motions occurred and Eurasia became almost stabilized. The formation of the Neogene back-arc basins in the Java Sea appears to date back to this 35 Ma event.

Cycles and patterns can be discerned in the geological development of Java. The Tertiary magmatic arc has shifted back and forth, from the southern boundary of present-day Java in Late Oligocene and Early Miocene times to northerly positions during the Upper Miocene and Lower Pliocene. A 'magmatic island arc loop' can be recognized in the stratigraphic record consisting of thick sequences of volcanic rocks in the lower parts of Miocene and Pliocene series, overlain by transgressive strata of marine claystones and marls without volcanics. In the upper parts of the series volcanics gain in importance, with mixed-marine settings trending towards continental deposition which is further accentuated by uplift caused by rising batholiths. Following uplift collapse and warp structures are formed before magmatism finally breaks through and closes the cycle.

Geologically, Java consists of a basement of both fossil tectonic melanges and continental crust, overlain by open folded Tertiary argillaceous rocks, locally with reef limestones, deposited in neritic environments intercalated by volcanic rocks. This sequence is partly capped by a thick pile of Quaternary volcanics which has led in most cases to foundation instabilities in the underlying plastic rocks.

In Chapter IV scale and time are further reduced to geological developments on Java during the Pleistocene. Widespread volcanism occurred during the this epoch, starting in the Lower Pleistocene in Central Java and western part of West Java. Geological evidence indicates the build-up of a regional magmatic arc from west to east during the Middle Pleistocene, marking the onset of the terrestrial setting known today. Most of these older volcanic cones suffered tectonic collapse and are topped by young volcanoes dating from the Late Pleistocene to Holocene. Three types of folding can be recognized: (a) an E-W trending simple fold system with steep axial surfaces driven by diapiric movements; (b) a regional E-W trending fold system with varying dips of axial surfaces accompanied by upthrust, faults and presumably also by décollement at deeper levels resulting from gravitational gliding against the central geanticline; (c) a highly complex local folding pattern around major volcanic cones, resulting from cone collapse and diapiric upbulging.

It is shown in this study that Java can be divided into more or less equal sized structural compartments, measuring about 200 km in width and bounded by deep-seated N-S trending transverse faults. These transverse faults have their continuation into the mosaic of high offshore basement blocks and basins in the Java Sea. Striking differences in geological structure, geomorphology, magmatism, position of volcanic lines, thickness of sedimentation, etc are found among these compartments or structural zones. The conspicuous coastal lowland shoreline fits remarkably well into this concept of structural compartmentalization.

The hilly hinterlands south of the coastal lowlands exhibit a remarkable cascade-like topography, frequently bounded by escarpments. Remnants of denudational planation surfaces are omnipresent at elevations of 30-50, 100-150 and 400-600 m, often veneered by younger reworked volcanics. The southern margin of the lowlands, which abuts abruptly against strongly folded Tertiary strata, coincides with the major regional tectonic hinge zone connecting the rising anticlinal of Java with the Quaternary marginal basins under the lowlands and Java Sea. Structures in the Tertiary strata under the lowlands and Java Sea consist of very gentle fold systems with broad domes. In contrast with this simple type of folding is the complexity of tectonic structure in Tertiary strata of the hilly hinterlands. This complexity increases dramatically northward approaching the hinge zone. Asymmetric folds, imbricated upthrusts and overthrusts, continuing into décollement zones at deeper levels dominate at the hinge zone. Geanticlinal uplift during the Pleistocene, reaching hundreds of metres, has been compensated by en-échelon normal faulting in the hinge zone. Secondary reactions to these uplift movements have been gravitational glidings of the sedimentary epiderm, promoted by the argillaceous and incompetent character of the strata. This has led to fault plane deformation of the first generation en-échelon faults, converting them into toppled-over normal faults by northward outward gliding and upthrust movements. The staircase-like topography is related to these systems of upthrust faults and is thought to continue under the southern margin of the lowlands.

Geological evidence for Pleistocene climatic fluctuations has been found in the form of (a) remnants of extensive planation surfaces in the hinterlands; (b) regolith mantles on the Prupuk and Blora reef limestones; (c) the allochtonous gravels in present-day stream valleys which slumped and slid into newly incised valleys from higher terraces; (d) high terraces on interfluves with cobble and boulder gravels; (e) decapitated or stripped soil profiles on planation surfaces; (f) indications of eolian deposition types in sediments of the Late Pleistocene Volcanic Fan Formation and doline fills in the Prupuk and Blora limestones.

Aspects of regional stratification in the sediment pile under the coastal lowlands are elaborated in Chapter V. Well-defined regional aquifers are lacking and tube wells tap water from at first sight chaotically arranged sandy clay- or silt layers encased in less permeable layers. Classical techniques of correlating lithological logs of large diameter wells or depths of local tube wells are generally bound to fail. However, statistical analyses applied to tube well depth data show three consistent horizons in all six kabupatens which are characterized by a significant probability of penetrating those thin more permeable layers. Frequency distributions in clusters of tube well bases in each of the three horizons approach a Gaussian probability distribution. Fitting a theoretical mixed frequency distribution of three Gaussian components by non-linear least squares regression yields three normal components with mean/standard deviation estimates of 48/11, 85/16 and 117/22 m depth.

Principally, flood plain clays and shelf muds are deposited under humid tropical conditions. These three more permeable horizons are thus thought to be associated with regional magmatic outbursts and drier climatic conditions, with different ETA (Erosion-Transport-Accumulation) systems capable of depositing sandy material at remote distances from the hinterlands.

Surface morphological features of the lowlands are discussed in Chapter VI. Statistical analyses of slope vectors for the almost featureless lowlands have revealed six well-defined clusters which coincide with the following morphological units:

1) Holocene coastal-/deltaic plain and lower flood plain elements with NNE vector trends;
2) southern sections of the flood plain belt and valleys incised in Late Pleistocene land surfaces with N vector trends;
3) dissected Late Pleistocene land surfaces and areas covered by Holocene piedmont deposits along the southern margins of the lowlands with low variability NNE vector trends;
4) landforms on volcanogenic fans and aprons originating from Ciremai volcano in kabupaten Cirebon;
5) Balapulang volcanogenic fan and piedmont plains around radial gravity gliding structures of Slamet volcano in kabupaten Tegal;
6) Holocene coastal-/deltaic plain and lower flood plain areas with variable slope vector trends and plunges.

All the earth scientific components described in Chapters III to VI are a prerequisite to understanding the intricate distribution of groundwater quality and flow systems. It is the main theme of this study is to show that groundwater flow systems in the lowlands are driven only by those morphological elements which possess a significantly higher terrain slope or, alternatively, by tectonic processes in the hinterlands which create sloping surfaces along the southern lowland margins. Furthermore, it is shown that a close relationship exists between the position of gravity generated groundwater flow systems and the six morphological coastal lowland units. Distinct morphological elements and geological processes giving rise to elevated and sloping topographies, capable of driving groundwater flow systems, may be listed as:

1) the Late Pleistocene Volcanic Fan Formation in West Java kabupatens and those areas covered by Holocene veneers;
2) Late Pleistocene/Early Holocene volcanogenic fans and mudflows of radial shape which flowed into the coastal lowlands. Notable examples are the Balapulang fan and lahar flows from Tangkuban Perahu volcano;
3) normal faulting in the major hinge zone, not followed by secondary gravitational reactions, which preserves fault scarps such as found in the Damar Formation near Weleri-Semarang;
4) sub-regional normal faulting transverse to major structural trends;
5) upthrusting of Quaternary sediments in the lowlands by gravitational gliding movements in the hinterlands and those deformations related to regional thrust structures or volcanic cone collapse and diapiric upbulging of the volcanic foot.

In Chapter VII the groundwater situation in the study area is depicted in a series of cross sections based on the expected geology, two deep wells in kabupaten Subang, the hydrochemical classification (Stuyfzand's method) of the tube well waters and flow paths as calculated with a finite-difference model FLOWNET. Most cross sections show that an original NaCl salt type of groundwater with salinities much less than those in pure seawater is found in the sediments. Flushing and processes of desalinization are only found under those parts of the lowlands where sufficient strong flow systems are generated by topographical elements at the surface. The general trend is towards desalinization and none of the hydrochemical types in the cross sections indicate salt water intrusion.

Coastal lowland settings dominated by broad coastal-/deltaic plains (morphological units 1 and 6) and narrow strips of the Late Pleistocene Volcanic Fan Formation or Holocene piedmont plains, such as found in the kabupatens Karawang, Indramayu and Brebes, are characterized by the extensive semi-stagnant groundwater bodies under morphological units 1 and 6. Groundwater flow systems are found only under the most southern strips and trends towards fresh $NaHCO_3$ types. Flow branches beneath the semi-stagnant bodies are too small to effectuate flushing. A different situation is met under coastal lowlands dominated by the Late Pleistocene Volcanic Fan Formation, which may be partly overlain by younger fans and lahars. Terrain slopes are sufficient to generate one or more flow systems in which important sub-regional branches emerge through windows in the narrow coastal plain. Semi-stagnant bodies are absent in these settings and mainly fresh $NaHCO_3$ water types are found. Impressive volcanogenic fans, such as the Balapulang fan in kabupatens Tegal and Brebes, are important topographical elements in generating far reaching groundwater flow systems. A fanhead and fan base flow system may occur as nested systems embedded in a sub-regional system. The sub-regional system ascends to the surface through broad windows in front of the fan base and is generally capable of flushing the deeper sediments to attain fresh $NaHCO_3$ water types. Notwithstanding the presence of terrain elements with sufficient topographical slopes, a shallow position of the Tertiary basement of mudstones underlying the lowlands, as found in kabupatens Tegal and Cirebon, may retard the generation of flow systems.

It is further shown in Chapter VII that the strongly mineralized shallow groundwaters in flood plain clays and silts are largely derived from mixing with connate saline pore water and dissolution of salts in these clayey materials which are derived by episodic erosion from Tertiary marine claystones, mudstones and marls in the hinterlands. Even the saline shallow groundwaters in the flood plains near the coast are totally unrelated to either encroaching saltwater tongues in rivers or the present Java Sea.

The self-flowing tube wells are driven by hydrostatic pressure excesses resulting from the load of the overburden of sediment layers. This load is still largely carried by the water. Sinking tube wells in these layers results in bleeding an overpressured system and accelerates the process of transferring the load from the water to the skeleton of mineral particles. This accelerated compaction is accompanied by the expulsion of saline pore waters which enter the well and constitute the main salinization mechanism, recognizable by a change from fresh $NaHCO_3$ to a fresh to brackish NaCl type.

SAMENVATTING

De studie behandelt de grondwatersystemen in de kustvlakte van Noord Java, Indonesië. Het studiegebied beslaat de kabupatens (Indonesische administratieve onderverdeling van een provincie), te weten van west naar oost: Karawang, Subang, Indramayu, en Cirebon in de provincie West Java en Brebes, Tegal in Midden Java. Geologisch zijn de kustvlakten opgebouwd uit voornamelijk kleiige sedimenten van Kwartaire ouderdom met een geschatte dikte van 200 tot 300 m, die zich ver uitstrekken onder de huidige ondiepe epicontinentale Java Zee. Typische sedimentaire afzettingsmilieus bestaan uit: ondiep marien, littoraal en kust-nabije gordels, deltas, uitgestrekte fluviatiele komgebieden, alluviale en vulkanogenetische puinwaaiers. Het grootste gedeelte van de sedimenten bestaat uit erosieprodukten afkomstig van geplooide Tertiaire fijn-korrelige marine sedimenten en Kwartaire vulkanische gesteenten in het heuvelachtige achterland. In de onderste gedeelten van het Kwartaire pakket zijn mogelijk nog erosieproducten vertegenwoordigd afkomstig van het Sunda kraton.

De exploitatie van grondwater wordt bemoeilijkt door lage permeabiliteiten en sterk variërende waterkwaliteiten zowel in vertikale als laterale zin. Sterk gemineraliseerde grondwatertypes komen zelfs voor in continentale afzettingen op tientallen kilometers van de huidige kust. In het algemeen wijkt het patroon van grondwaterkwaliteit sterk af van het klassieke concept van kust-aquifers met eenduidige scherpe zoet-zout grenzen.

Ten einde een beter begrip te verkrijgen van de ingewikkelde grondwaterhydrologie is gekozen voor een aardwetenschappelijke benadering, waarbij de geologische ontwikkelingen op Java, gezien vanuit breed kader in schaal en tijd, zijn gevolgd tot op het lagere hiërarchische niveau van huidige kustvlakte-afzetting. De hoofdgedachte van hiërarchische reductie beginnend bij een referentiepunt hogerop in de systeemhiërarchie, die hier achter schuilt is gelegen in het feit dat de hydrogeologische complexiteit van de kustvlakte verband houdt via een gevolg-oorzaak effect met geologische en tectonische ontwikkelingen in het achterland in een veel breder kader. Veel aandacht is besteed in deze studie aan het opsporen van die geologische, morfologische en pedogenetische kenmerken in het heuvelachtige achterland, waaruit de afzettingsgeschiedenis en omstandigheden waaronder afzetting heeft plaatsgevonden kunnen worden afgeleid.

Hoofdstuk I geeft een overzicht van de fysische aspecten van uitgestrekte kustvlakten in de natte tropen en de vaak daarmee gepaard gaande grote bevolkingsdichtheden als gevolg van natte rijstbouw. Vanuit historisch en cultureel oogpunt hebben de kustvlakten op Java en de brede alluviale vlakten in sommige delen van de centrale depressiezone, een zeer belangrijke rol gespeeld bij zuidwaarts gerichte migratiegolven van bevolkingen uit het vasteland van Azië.

De gevolgde methodologie en het systeemconcept zijn uitgewerkt in Hoofdstuk II. Het blijkt dat het geologische kader waarin processes actief zijn geweest, relevant voor het bestudeerde gebied, zich uitstrekt tot op de schaal van een schollentectonische rand en een tijdsspanne vanaf het begin van het Tertiair. De geologische ontwikkelingen zijn gevolgd door af te dalen langs een dendritische structuur in tijdspanne en ruimtelijke schaal. Bij iedere afdalingsstap langs de takken van de boomstructuur worden tijdspanne en schaal verder gereduceerd. Belangrijk is het effect van mogelijke overerving van eigenschappen van objecten op een hogere rang in the hiërarchische structuur door objecten op lager niveau. Speciale aandacht is besteed aan het probleem van Kwartaire klimaatswisselingen op Java en de te verwachten relicten van polygenetische landvormen en het uiteindelijke effect van deze fluctuaties op de ontwikkelingen in de sedimentaire randbekkens.

De Tertiaire evolutie van Java wordt behandeld in Hoofdstuk III aan de hand van een subductiezone in moderne schollentectoniek, waarin tevens een beschrijving wordt gegeven van de belangrijkste elementen in het subductiesysteem. Een geologische beschrijving wordt gegeven van fossiele tectonische melanges van een Laat Krijt tot Vroeg Tertiaire ouderdom, ontsloten in Bayat en Karangsambung in Midden Java. Gedurende de formatie van deze melange-wiggen was de vulkanische lijn ongeveer gelegen ter hoogte van de zuidelijke kust van de huidige Java Zee. Een opmerkelijke tectonisch rustig periode volgt dan van Midden Eoceen tot Laat Oligoceen, reeds opgemerkt door andere onderzoekers, die zich kenmerkt door afzetting van silicaklastische gesteenten en rifkalkstenen zonder vulkanisme. In deze studie wordt deze opmerkelijk rustige periode zonder magmatisme in de gordel van het huidige Java in verband gebracht met een wereldwijde reorganisatie van schollenconfiguraties, waarbij ook de oceanische spreidingsruggen in de Indische Oceaan betrokken zijn geweest. Van 80 to 54 miljoen jaar geleden bevond zich een actieve oceanische spreidingsrug op een afstand van waarschijnlijk niet meer dan 3.000 km ten zuiden van Java. Deze rug was verantwoordelijk voor subductie, vorming van de tectonische melanges ontsloten in Bayat en Karangsambung en de vulkanische lijn in de huidige Java Zee. Rond 54 miljoen jaar geleden vond er een volledige reorganisatie plaats van spreidingsruggen in de Indische Oceaan, hetgeen leidde tot het wegvallen van de rug tussen Eurazië en Australië naar een nieuwe positie tussen Australië en Antarctica, waarvan wordt aangenomen dat deze verplaatsing een effect heeft gehad op de subductiesnelheden langs de Java Trog. Subductie heeft zich waarschijnlijk grotendeels weer hersteld vanaf 34 miljoen jaar geleden toen drastische veranderingen in schollenbewegingen zich voordeden in de Stille Oceaan en de bewegingen van het Euraziatische continent vrijwel gestabiliseerd waren. Het ontstaan van de Neogene back-arc basins in de Java Zee dateert waarschijnlijk van deze schollentectonische gebeurtenis rond 34 miljoen jaar.

Cyclussen en vaste patronen kunnen worden herkend in de geologische ontwikkeling van Java. De Tertiaire vulkanische lijn heeft zich verplaatst van een positie evenwijdig aan de huidige zuidkust van Java in het Laat Oligoceen/Vroeg Mioceen naar meer noordelijk gelegen posities in het Boven Mioceen/Onder Plioceen. Een 'vulkanische eilandenboog cyclus' is te herkennen in de stratigrafische ontwikkeling van Java, bestaande uit dikke vulkanische series in het Onder Mioceen en Onder Plioceen, gevolgd door dikke pakketten van transgressieve mariene klei-, siltstenen en mergels zonder vulkanische inschakelingen. Boven in de Miocene en Pliocene series verschijnen wederom enige vulkanische afzettingen en verandert het afzettingsmilieu van open marien via uitgestrekte moerassige kustvlakten naar een continentale omgeving waarbij opheffing door rijzende batholieten merkbaar worden. Na opheffing volgen tectonische inzakkingen en het scheef stellen van lagen, waarna magmatisme aan het oppervlak verschijnt en vulkanische kegels worden opgebouwd met overheersend vulkanische afzettingen en de cyclus zodoende wordt gesloten. Geologisch bestaat Java uit een ondergrond van fossiele tectonische melanges en kristallijne gesteenten, afgedekt door open geplooide Teriaire kleiige gesteenten, lokaal met rifkalkstenen, afgezet in neritische mariene milieus, met inschakelingen van vulkanische gesteenten. Op dit Tertiaire pakket volgen in gordels dikke vulkanische afzettingen van Kwartaire ouderdom, hetgeen in veel gevallen heeft geleid tot fundatieproblemen in onderliggende plastische gesteenten die vaak zijn uitgeknepen onder grote vulkaankegels.

In Hoofdstuk IV zijn schaal en tijd verder gereduceerd tot de geologische ontwikkelingen op Java gedurende het Pleistoceen. Wijd verspreide vulkanische activiteiten hebben zich voorgedaan tijdens dit tijdvak, beginnend in het Onder Pleistoceen in Midden Java en westelijk gedeelte van West Java. Geologische gegevens wijzen op een regionale ontwikkeling van een magmatische rug van west naar oost gedurende het Midden Pleistoceen, hetgeen de eerste stap markeerde naar de huidige continentale omgeving. De meeste van deze oude vulkaankegels hebben naast normale erosie nog te lijden gehad van tectonische verzakkingen en wat overbleef aan vulkaanruines is wederom overkapt met jonge kegels van Laat Pleistocene tot Holocene ouderdom. Drie hoofdtypen van deformatie kunnen worden onderscheiden: (a) een oost-west gericht simpel plooiingssysteem met steile assenvlakken gevormd door diapiere bewegingen van plastische onderliggende gesteenten; (b) een oost-west gericht plooiingssysteem met gevarieerd hellende assenvlakken gepaard gaande met opschuivingsbreuken en waarschijnlijk décollement op diepere niveaus als gevolg van het gravitatief afglijden van de sedimentaire epiderm langs de geanticlinaal; (c) een zeer complex lokaal plooiingspatroon rondom grote vulkaankegels, als gevolg van inzakking van de kegeltop en het diapier oppersen van plastische gesteenten aan de kegelvoeten.

In deze studie wordt aangetoond dat Java kan worden opgedeeld in structurele compartimenten van min of meer gelijke afmeting, ongeveer 200 km breed in een oost-west richting en begrensd door diepe noord-zuid gerichte transversale breuken. Deze diepe noord-zuid gerichte breuken zijn te vervolgen in het mozaïek van horsten en slenken in de kristallijne ondergrond van de Java Zee. Opmerkelijke verschillen in geologische structuur, geomorfologie, magmatisme, positie van vulkanische lijnen, dikte van sedimenten etc. bestaan er tussen deze structurele transversale zones. De markante kustlijn van de laaglanden blijkt goed aan te sluiten op deze configuratie van structurele compartimentering.

Het heuvelachtige achterland ten zuiden van de kustvlakten vertoont een opmerkelijke cascade-achtige topografie, vaak begrensd door klifvormige treden. Overblijfselen van vlakke denudatiereliëfs zijn alomtegenwoordig op hoogten van 30-50, 100-150 en 400-600 m vaak nog bedekt met een dunne laag jonge verspoelde vulkanoklastische afzettingen. De zuidrand van de kustvlakte die abrupt doodloopt tegen de sterk geplooide Tertiaire lagen, valt samen met de regionale tectonische scharnierzone die de oprijzende geanticlinaal van Java verbindt met de Kwartaire randbekkens onder de kustvlakte en de Java Zee. De structuren in de Tertiaire lagen onder de laaglanden en de Java Zee bestaan uit een licht golvende zeer open plooiing met brede dôme structuren. Deze vlakliggende vrijwel ongedeformeerde lagen contrasteren sterk met de complexiteit van structuren in de Tertiaire gesteenten in het heuvelachtige achterland. De complexiteit neemt noordwaarts sterk toe bij het naderen van de scharnierzone. Asymmetrische plooiing, opschuivingen met verschubbingen en overschuivingen overgaand in décollement op diepere niveaus, overheersen in de scharnierzone. De geanticlinale opheffingen gedurende het Pleistoceen die honderden meters hebben bereikt zijn gecompenseerd door en-échelon afschuivingsbreuken in de scharnierzone. Secundaire reacties op deze opheffingen hebben bestaan uit gravitatieve afglijdingen van de sedimentaire epiderm, hetgeen nog versterkt is door het kleiige en incompetente karakter van deze epiderm. Dit alles heeft geresulteerd in de ombuiging van de bovenkant van breukvlakken, behorende tot eerste generatie en-échelon breuken, door noordwaartsgerichte gravitatieve verglijdingen en opschuivingen. De cascade-achtige topografie houdt verband met deze tectoniek van verschubbingen en opschuivingen en zet zich waarschijnlijk voort tot onder de zuidelijke rand van de kustvlakten.

Geologisch bewijsmateriaal voor Pleistocene klimaatswisselingen zijn gevonden in de vorm van (a) overblijfselen van uitgestrekte vlakke denudatiereliëfs in het achterland; (b) regolietmantels rondom de Prupuk en Blora kalkstenen; (c) gestorte allochtone grinden in de huidige rivier- en beekdalen afkomstig van hogere terrassen behorende tot de denudatiereliëfs; (d) hoogterrassen op de waterscheidingsruggen met bedekkingen van kei- en blokkengrind; (e) onthoofde bodemprofielen op de denudatiereliëfs; (f) indicaties van eolische afzettingsmilieus in sedimenten van de uitgestrekte Laat Pleistocene Vulkanogene Formatie en in de doline-opvullingen van de Prupuk en Blora kalkstenen.

Aspecten van regionale gelaagdheid in de sedimentpakketten onder de huidige kustvlakte zijn uitgewerkt in Hoofdstuk V. Scherpbegrensde, lateraal correleerbare aquifers ontbreken en de stalen draadpijpputten (tube wells) onttrekken grondwater van op het eerste gezicht chaotisch verdeelde dunne zandige klei- en siltlagen, omgeven door aanzienlijk minder permeabele lagen. Klassieke technieken van laterale correlaties tussen lithologische boorgatbeschrijvingen van geboorde putten of correlaties tussen einddiepten van draadpijpputten blijken gewis uit te lopen op mislukkingen. Daarentegen toont statistische analyse van einddiepten van draadpijpputten wel de aanwezigheid aan van drie consistente horizonten, in de zes bestudeerde kabupatens, die worden gekenmerkt door een significant hogere kans op het aantreffen van dunne zandige kleilagen of lenzen met een dusdanig hogere permeabiliteit waaraan water kan worden onttrokken door draadpijpputten. Frequentieverdelingen in einddiepten in groepen van draadpijpputten in ieder van de drie horizonten benaderen een Gauss kansverdeling. De samenhang tussen frekwenties in einddiepten van draadpijpputten en een theoretische drie-componenten Gauss kansverdeling onderzocht met non-lineaire regressie volgens de kleinste kwadratenmethode heeft drie Gauss componenten in de putgegevens opgeleverd met gemiddelde/standaard deviatie schattingen van 48/11, 85/16 en 117/22 m diepte.

Onder humide tropische omstandigheden worden echter hoofdzakelijk fluviatiele kleien en mariene kleien op het continentale plat afgezet. De drie regionale horizonten met hogere permeabiliteit worden dan ook gerelateerd aan regionale verhoogde magmatische activiteit en de effecten van drogere klimaatsomstandigheden waarbij ETA (Erosie-Transport-Accumulatie) systemen dusdanig worden gewijzigd waardoor zandige materialen kunnen worden afgezet op grote afstanden van het achterland of eruptiecentra.

De uiterlijke morfologische kenmerken worden besproken in Hoofdstuk VI. Statistische analyses van terreinvectoren in de ogenschijnlijk vlakke laaglanden hebben zes duidelijke groeperingen aangetoond welke samenvallen met de volgende morfologische eenheden:

1) Holocene fluviomariene kust- en deltavlakten en lagere delen van fluviatiele komgebieden, terreinhellingsrichting voornamelijk NNO;
2) zuidelijke gedeelten van fluviatiele komgebieden en dalen ingesneden in de Laat Pleistocene landoppervlakken, voornamelijk N terreinshellingsrichtingen;
3) versneden Laat Pleistocene landoppervlakken, zowel bedekt als onbedekt door dunne Holocene voetvlakafzettingen, langs het zuidelijk gedeelte van de laaglanden, geringe variabiliteit in de NNO gerichte hellingen;
4) landvormen op vulkanogene puinwaaiers en laharstromen afkomstig van de Ciremai vulkaan in kabupaten Cirebon;
5) de vulkanogene puinwaaier van Balapulang en voetvlakken aan het uiteinde van de radiale gravitatieve verglijdingsstructuren van de Slamet vulkaan in kabupaten Tegal;

6) Holocene fluviomariene kust- en deltavlakten en lagere delen van fluviatiele komgebieden, zeer variabel in helling en hellingsrichting van het terrein.

Het doorgronden van elementen van aardwetenschappelijk karakter, zoals beschreven in de Hoofdstukken III tot en met VI die ogenschijnlijk los staan van de grondwatersituatie in de kustvlakten, blijkt een eerste vereiste te zijn bij de ontwarring van de ingewikkelde verdeling van grondwaterkwaliteit en stromingssystemen. Het is het hoofdthema van deze studie om aan te tonen dat grondwaterstromingssystemen in de kustvlakten worden aangedreven slechts door die morfologische elementen die een significant hogere terreinhelling bezitten of indirect door tectonische processen in het achterland die aanleiding geven tot significant hogere hellingen in de voetvlakken langs de zuidelijke rand. Bovendien is aangetoond dat er een nauwe relatie bestaat tussen de positie van gravitatief aangedreven grondwaterstromingssystemen en de zes eenheden in kustvlaktemorfologie. Morfologische elementen en geologische processen die resulteren in significant grotere topografische hellingen in de kustvlakte, ter aandrijving van grondwaterstromingssystemen zijn:

1) de Laat Pleistocene Vulkanogene Formatie in de kabupatens in West Java en die gedeelten van de Formatie bedekt met dunne Holocene afzettingen;
2) Laat Pleistocene/Vroeg Holocene vulkanogene puinwaaiers en laharstromen met radiale vormen die vanuit de achterlanden de kustvlakten zijn binnengestroomd. Bekende voorbeelden zijn te vinden in de Balapulang waaier en de laharstromen van de Tangkuban Perahu vulkaan;
3) sub-regionale afschuivingsbreuken in de scharnierzone zonder secundaire gravitatieve reacties van de achterliggende plastische epiderm, waarbij verschuivingskliffen intact zijn gebleven zoals worden aangetroffen in de Damar Formatie bij Weleri en Semarang;
4) afschuivingsbewegingen transversaal op de richting van de hoofdstructuur;
5) opschuivingen en opdrukkingen van Kwartaire sedimenten in de laaglanden door gravitatieve verglijdingen in het achterland en bewegingen die gerelateerd zijn aan inzakkingen van vulkanische kegels en diapiere oppersingen in kegelvoeten.

In Hoofdstuk VII is de grondwatersituatie van het studiegebied afgebeeld in een aantal noord-zuid gerichte dwarsdoorsneden gebaseerd op de te verwachten geologie, twee diepe boorgaten in kabupaten Subang, hydrochemische classificatie (Stuyfzand methode) van de watermonster uit draadpijpputten en stromingsbanen berekend met een verticaal eindig-elementen model FLOWNET. Alle dwarsdoorsneden tonen aan dat een oorspronkelijk NaCl type grondwater aanwezig is geweest met saliniteiten ver beneden die van puur Java zeewater. Uitspoeling en ontziltingsprocessen worden alleen aangetroffen onder die gedeelten van de kustvlakten waar voldoend sterke stromingssystemen worden gegenereerd door topografische elementen aan de oppervlakte. De algemene tendens is er een van ontzilting en geen van de hydrochemische types aangetroffen in het studiegebied wijst op zoutwaterintrusies.

Gedeelten van de laaglanden die worden gedomineerd door brede fluviomariene kust- en deltavlakten (morfologische eenheden 1 en 6) en een relatief smal ontsloten rand van de Laat Pleistocene Vulkanogene Formatie of smalle Holocene voetvlakken, zoals het geval is in de kabupatens Karawang, Indramayu en Brebes, zijn gekenmerkt door uitgestrekte semi-stagnerende grondwaterlichamen zich bevindend onder de morfologische eenheden 1 en 6. Grondwaterstromingssystemen zijn beperkt tot de meest zuidelijke strook waar de voetvlakken of de Vulkanogene Formatie dominant zijn en hebben daar geleid tot zoete $NaHCO_3$ types van grondwater. Stromingstakken onder de semi-stagnerende lichamen hebben een te geringe flux om ontzilting tot stand te brengen.

Een totaal verschillende situatie wordt aangetroffen onder laaglanden die morfologisch worden gedomineerd door de Laat Pleistocene Vulkanogene Formatie, welke nog gedeeltelijk bedekt kan zijn met jongere waaiers of laharstromen. Terreinhellingsgradienten zijn voldoende om een of meer stromingssystemen te genereren, waarbij belangrijke sub-regionale stromingstakken doorbreken in vensters in smalle strips langs de kust. Stagnerende grondwaterlichamen zijn afwezig in deze omgeving en hoofdzakelijk zoete $NaHCO_3$ grondwatertypes worden aangetroffen. Imposante vulkanogene puinwaaiers als de Balapulang waaier in de kabupatens Tegal en Brebes zijn belangrijke morfologische elementen in het genereren van verreikende grondwaterstromingssystemen. Locale stromingssystemen aan de top en basis van de vulkanogene waaier komen voor die gesuperponeerd zijn op een sub-regionaal systeem. De opwaartse stroomlijnen van dit sub-regionale systeem komen aan de oppervlakte in een breed venster langs de waaierbasis en dit stromingssysteem is in het algemeen in staat geweest een ontzilting tot stand te brengen tot zoete $NaHCO_3$ types. Ondanks de aanwezigheid van terreinelementen met substantiële topografische hellingen zijn ondiepe posities van Tertiaire kleistenen en mergels onder de laaglanden, zoals dat het geval is in de kabupatens Tegal en Cirebon, in staat stromingssystemen volledig te blokkeren.

In Hoofdstuk VII wordt verder aangetoond dat de sterk gemineraliseerde ondiepe grondwateren in de fluviatiele komkleien grotendeels afkomstig zijn van menging met zout connaat poriënwater en oplossing van zouten in deze kleiige materialen afkomstig van episodische erosie van Tertiaire mariene klei-, siltstenen en mergels uit het achterland. Zelfs tussen de saline ondiepe grondwateren in de komkleien vlakbij de huidige kust en de naar binnendringende zeewatertongen op de belangrijkste rivieren of de huidige Java Zee bestaat geen aanwijsbaar verband.

De zelfstromende draadpijpputten in de laaglanden worden gedreven door hydrostatische overdruk als gevolg van belasting door bovenliggende sedimentlagen waarbij deze belasting, in plaats van door het korrelskelet, nog grotendeels wordt gedragen door het interstitiële water. Het aftappen van grondwater door draadpijpputten in deze diepere lagen met wateroverspanning resulteert in een versneld afvloeien van de wateroverspanning waardoor de spanning op het korrelskelet eveneens versneld toeneemt. Deze versnelde consolidatie gaat vergezeld van het uitpersen van zout porienwater uit de omringende mariene kleien hetgeen het belangrijkste verziltingsproces vormt herkenbaar aan de overgang van zoete $NaHCO_3$ types naar zoet tot brakke NaCl grondwatertypes.

I. *INTRODUCTION*

1.1 *General aspects of coastal lowlands in the humid tropics*

The affinity of man for riverine locations is one of the outstanding features of human settlement patterns; low-relief lands adjacent to rivers have attracted dwellers throughout history. Given a favourable climate, man and his settlements will be restricted to non-mountainous areas where there is a flat or gently undulating topography, a reliable water source and a rich alluvial soil suitable for settlement and cultivation. In particular the ecologically-favourable broad flood plains in the lower reaches of rivers and river deltas, have played important roles in providing sites for many great civilizations. In the low-latitude belt with the tropical rainy climates, striking examples of such great civilizations are found in Southeast Asia, for example the great hydraulic societies in India and China. Rice is the staple food in these lowland areas, due to the fact that it is the only cereal which can be cultivated in swampy lands. The ease with which rice can be grown in these originally swampy lowlands has generally led to dense populations. Braudel (1977), mentions an intensive colonization within the borders of China already at the end of the 17th century, in which all the low-lying lands and hills that could be irrigated were developed. The reasons are fairly obviously related to the rich alluvial soils and the relatively flat topography, constituting the main ingredients for development of a thriving agriculture. Aspects of transport and accessibility to road systems and the broad slow streams for boat traffic are other reasons that influence human settlement. Many irrigation projects are located on these broad flood plains and upper deltaic areas. If drainage is adequately secured, these lowland areas are readily cultivated and irrigation works can be fed simply by impounding water from natural channels.

Systems of these gently undulating flood plains and upper deltaic plains may coalesce into extensive coastal lowlands, occupying large areas and producing thick deposits of fluvial or marine origin. Large rivers like the Indus, BrahmaPutra-Ganges, Irrawaddy, Me Nam, Mekong, Red River (or Coi), and smaller ones like the Cimanuk and Citarum in Java have built up extensive coastal lowlands. The heavy sediment loads of the rivers in humid tropical areas favour the development of rapidly outbuilding coastal lowlands. Due to the combination of high temperatures and torrential rainfall, the rivers in Southeast Asia tend to carry extremely heavy sediment loads and the formation of deltas proceeded with great rapidity during historical times. In particular those rivers which transport their loads into shallow seas on continental shelves develop extensive coastal lowlands.

Placed in a broader context of racial ancestry and cultural development of the population in the Indonesian Archipelago today, Fisher (1971) points out the crucial role played by the riverine- and coastal lowlands in affording human migrations and settlements. Settlers and pioneers coming into the region from the sea will find favourable natural circumstances to support wet-rice cultivation as practised by the Mongoloid invaders. Waves of southerly migrations have taken place in which the invaders seized the better coastal- and riverine lowlands for themselves, pushing the earlier inhabitants into the mountains or the remoter islands in the eastern part of the Archipelago. Thus Fisher (1971) further notes that the coastal fringes and riverine lowlands in the western part of the Archipelago have been predominantly areas of cultural change and replacement. This has led to the fundamental contrast of the coastal and riverine lowlands on the one hand and the interior uplands and remoter Indonesian islands on the other. Impacts of Indian and Chinese civilizations have been limited exclusively to these lowland areas.

A major drawback of coastal lowlands in monsoonal regions is the vulnerability to severe flooding, which may lead to recurrent loss of lives and property. As such, the technical control and regulation of water to prevent flooding in monsoonal coastal lowlands is more important than water availability or nutrient input. However, the threat of sometimes yearly flooding has not prevented or discouraged human settlement in these regions. On the contrary, most coastal lowland areas are coping with severe problems of high density populations, though alternative areas may not be readily at hand since all the ecologically-favourable areas are already cultivated. The supply of food for a burgeoning population, in which consumption outstrips agricultural developments in raising production, requires the coastal lowlands to be fully cultivated. On the other hand, moderate floods have been a blessing in the days of ancient indigenous irrigation systems, when cultivation of the wet variety of rice in coastal lowlands depended on river regimes with warm season floodings. Flood protection in low-gradient rivers with huge sediment loads becomes difficult in violent tropical monsoonal- and tropical wet-dry regimes (Koppen regions Am and Aw, respectively). Notably, rivers draining vast catchments in the mountainous hinterlands have the peculiarity of flowing between natural, raised levees, almost above the surrounding flood plains in lower parts of the coastal lowlands. The construction of major technical irrigation works at the beginning of this century comprising a dense network of channels and intakes, has greatly lessened flooding. Once the main arteries in the irrigation networks were established and the major technical flood control works erected, occupation of the coastal lowlands took place rapidly.

Newly formed or emerged parts of coastal lowlands possess poor natural drainage systems, giving rise to vast fresh water swamps. Depending on sediment supply and tidal range, coastal fringe mangrove swamps may develop. In this virgin scenery of coastal lowlands, the most attractive locations for settlement must have been the raised natural levees of major streams and the beach ridges. Reclamation of the swampy areas has gradually widened the opportunities for settlement. Present-day problems are the centres of heavy urbanization in coastal lowlands with their variety of ecological difficulties such as surface water supply, groundwater withdrawals and land subsidence.

From a geological point of view, coastal lowlands are formed in complex sedimentary environments by unconsolidated terrestrial and marine deposition. The unstable balance between non-marine and marine environments, as evidenced by the ever-shifting coastlines, is very sensitive to changes in sediment supply from the hinterland, sea level changes and vertical tectonic movements. Generally, extensive coastal lowlands bordering shallow cratonic seas exhibit complex alternating patterns of deeply interfingered fluvial and marine beds. In humid tropical settings suspended sediment supply is mostly sufficient to result in a net outbuilding of coastal lowlands. Depending on the hinterland geology, sediments in such humid tropical settings are predominantly clayey and silty. Changes in climate and global sea level during recent geological history must have had profound effects on the building of coastal lowlands.

Groundwater conditions in extensive humid tropical coastal lowlands are closely related to the overall clayey and silty character of the sediments. Hydraulic gradients are far too small and permeabilities are usually too low, to ensure adequate groundwater flows which might flush the sediments. In general, fairly unfavourable groundwater conditions are met. Shallow and deep groundwaters may be highly mineralized and not suitable for human or livestock consumption, even at great distances from a present-day coastline. Groundwater quality is highly variable both laterally and in depth, apparently without definite patterns. On the whole domestic water supply becomes increasingly difficult in the lower parts of the coastal lowlands. Groundwaters suitable for human consumption may be absent, in which case rural populations are forced to use surface water resources found in polluted irrigation networks or turbid rivers.

Multiple aquifer systems are generally encountered in coastal lowlands with deeper sources even sustaining self-flowing wells. However, it is usual that these hydraulic heads, which may have risen initially above ground level, are steadily declining since the first well were drilled. Heavy urbanization also gives rise to large scale extraction of groundwater, often accompanied by problems of land subsidence.

1.2 Geography of the area of investigation

The Indonesian archipelago is situated between the Indo-China peninsula and the Australian continent, thereby extending over about 47 degrees of longitude (from 94°45' to 141°05' longitude east) and slightly more than 18 degrees in latitude (from 6°08' latitude north to 11°15' latitude south). The area resembles a rectangle measuring 5,000 km in length and 2,000 km in width, which is traversed by the equator. According to Hardjono (1971) about 3,000 significant islands lie in this vast rectangle and the same author also estimates a total number of 13,667 islands, if the smallest atols are included.

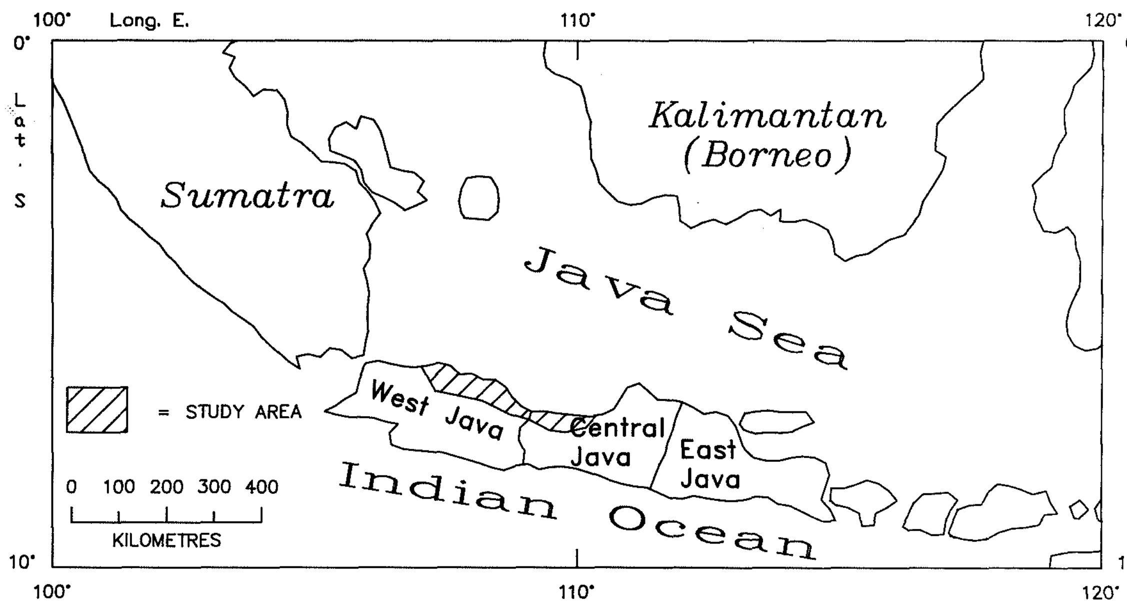


Fig. 1.1 General location map.

The archipelago exhibits a wide range of submarine and terrestrial relief, arranged more or less concentrically around an old Mesozoic nucleus represented by the island of Kalimantan (Borneo), the eastern part of the island of Sumatra and the Malaysian peninsula. Two arcs can be distinguished, i.e. a volcanic inner arc and a non-volcanic outer arc. The outer arc, although omnipresent, emerges above the sea in certain stretches only.

The humid tropical climate of the Indonesian Archipelago is characterized by a constancy in temperature and humidity. Over almost the entire Archipelago the mean temperature of the coldest month is still above 20^{0}C and the total annual rainfall more than 2,000 mm. Mean annual temperatures at sea level range between 26 and 28^{0}C. Fontanel and Chantefort (1978) mention a mean thermic amplitude of about 2^{0}C only for the major areas.

Although the Archipelago belongs to monsoonal Asia, featuring an equatorial and tropical type of monsoon (Fisher, 1971), a dry season is evident in Central Java to Irian Jaya (West New Guinea) and including the southern parts of Sulawesi (Celebes). The entire insular domain is situated within the belt of the annual shifting Intertropical Zone of Convergence (ITC) where the trade winds of both hemispheres meet. The shift of the ITC is controlled by the anticyclonal systems above Central Asia and Australia. In January the ITC is positioned approximately above Australia and wind circulation is generated by the high pressure areas in Central Asia, giving rise to the wet N-E and N-W monsoonal winds in the Archipelago, respectively north and south of the equator. The wind circulation is reversed in July with winds generated by the high pressure areas in Australia, during which the ITC shifts up to China. These southeast monsoonal winds are dry coming from the Australian continent, which explains the dry season of those parts of the Archipelago nearest to Australia.

The area of investigation is situated in the coastal lowland belt on the northern side of the island of Java, bordering the Java Sea, between the eastern longitudes 107^0 and 109^{0}25' (Fig. 1.1). The area comprises the kabupatens[1] (enumerated from west to east): Karawang, Subang, Indramayu and Cirebon in the province of West Java and the kabupatens Brebes and Tegal in the province of Central Java.

The island of Java with a total area of 127,000 km^2 (132,000 km^2 including Madura) coincides with the volcanic inner arc. The crest of the outer arc, situated to the south of the island, is a totally submarine feature in the vicinity of Java. Beyond the outer arc the deep marine Java trench can be found, descending to depths of 6,000-7,000 m. Both major and minor earthquakes occur frequently in the Indonesian region and are mostly related to the oceanic plate subduction near the deep marine trench.

A belt of Quaternary strato-volcanoes is aligned along the longitudinal E-W axis of the island and dominates the morphology of the island. Numerous summits of symmetrically-shaped volcanoes rise above 3,000 m. From the total of 121 volcanoes on Java, 15 cones exceed 3,000 m and about 25 volcanoes are still active. The almost continuous central volcanic belt is superimposed upon older marine strata of Tertiary age. These are irregularly folded and are primarily composed of neritic (mostly inner neritic) marine, fine-grained sediments intercalated with volcanogenic sediments.

A threefold geomorphological division in E-W trending zones on Java gives:

---

1 A kabupaten is an administrative subdivision of a province. The island of Java is divided into three provinces, viz. West-, Central- and East Java, comprising a total of 82 kabupatens. Each kabupaten is further subdivided into kecamatans and municipalities. Kecamatans are further divided into desas.

1) a northern zone comprising low hilly areas overlying folded Tertiary strata, and the Quaternary coastal lowlands bordering the Java Sea;
2) a central depression filled with Quaternary volcanics. The majority of great volcanic cones lie within this structural zone;
3) a southern zone of uplifted and tilted plateaus of Tertiary strata, dissected by narrow coastal lowlands.

In the central volcanic arc several intramontane plains, with E-W trending longitudinal axes and broad transverse valleys can be distinguished. At the southern flank of the central volcanic arc a hilly to mountainous area occurs designated by Van Bemmelen (1949) as the Southern Mountains, rimmed by narrow patchy coastal lowlands. These narrow coastal lowlands are interrupted by raised plateaus with cliffs or hilly terrains rising steeply from the sea. The broad coastal lowland belt in the northern zone is of variable width; the broadest parts are found in West Java and the narrower parts in Central Java.

Three principal types of terrain can be distinguished on Java, related to morphology and geology, viz.: (see Fig. 1.2)

1) alluvial plains and coastal lowlands;
2) Quaternary volcanic terrains;
3) Tertiary sedimentary terrains.

In West Java the northern coastal lowlands may be as broad as 40 km and narrow towards the east, due to the abruptly inflecting coastline between Indramayu and Cirebon, and measure about 3 km near the town of Cirebon (Fig. 1.2). They can be traced further into Central Java with an average width of 20 km. Beyond the northern coastal lowland belt lies the shallow Java Sea, covering the Sunda shelf which is just a submerged craton. In the central zones of the Java Sea depths of about 50 m occur, with maxima of 80 m in fluviatile sculptured valleys formed during Pleistocene glacial periods with low eustatic sea levels. Most of the drainage of Java is directed towards this sheltered inner sea (Fig. 1.3). Sharply contrasting with the submarine morphology of the Java Sea is the deep Indian Ocean on the southern side of Java, reaching average depths of 5,000 m.

Many protruding deltas can be identified along the northern coastal lowland belt and the shoreline is dominated by the huge influx of land-derived sediments, resulting in rapidly accreting coastal/deltaic plains. Several large rivers such as the Citarum, Cimanuk and Kali Pemali draining vast intramontane basins in the central volcanic magmatic belt, have built conspicuous bird-foot type deltas (Fig. 1.3.)

The northern coastal lowland area is densely populated with average rural densities ranging from 500 to 1,600 inhabitants per km^2 (Penduduk Indonesia 1985 menurut provinsi, Biro Pusat Statistik, Jakarta). Heavily urbanized areas are to be found mainly around Jakarta and Semarang. In the Jakarta-Bogor area population densities largely exceed 10,000 inhabitants per km^2. In general a rural setting prevails in the area. In West Java at least half of the population inhabits the northern coastal lowlands. The larger part of the area is situated below the approximately 25 m height contour and is almost entirely used for intensively irrigated rice cultivation. A dense network of irrigation canals dissects the area to sustain in most parts the wet mono-culture of rice practiced the year around.

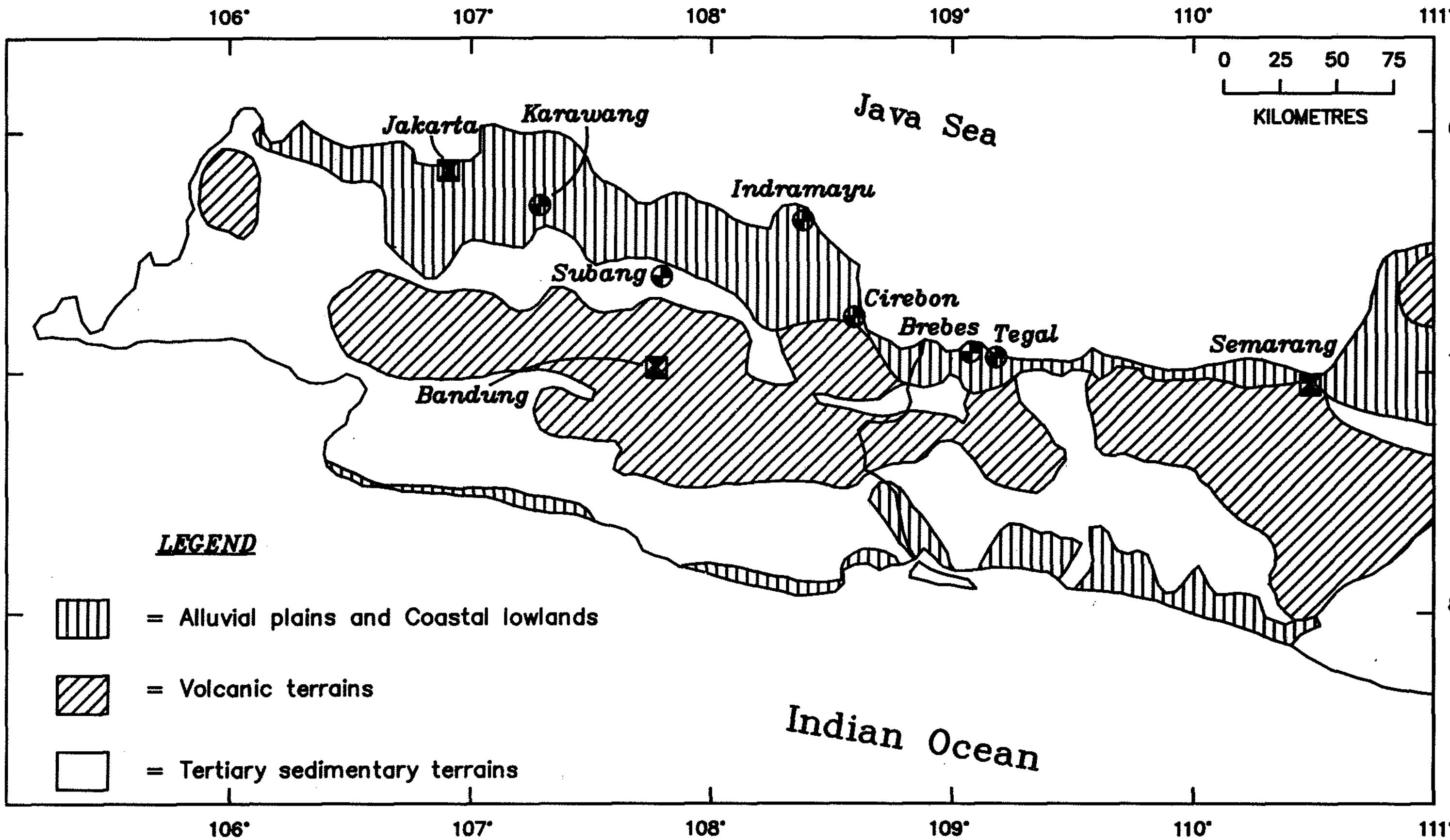


Fig. 1.2 The principal terrain types on Java.

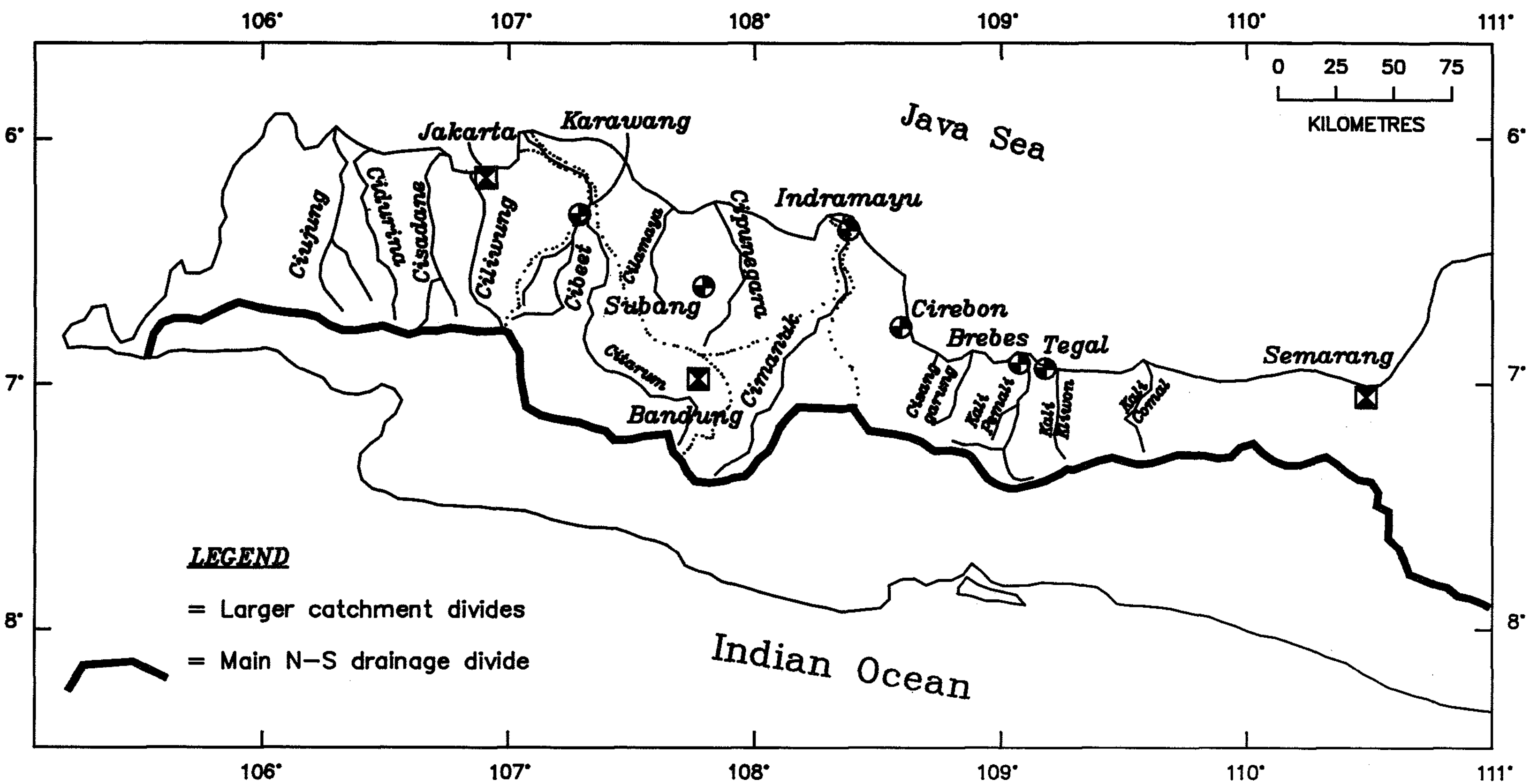


Fig. 1.3 Major drainage systems in the northern part of Java.

1.3 *Problems in the northern coastal lowlands of Java*

1.3.1 *Aspects of Human Inhabitation*

In the study of hydrological aspects of the northern coastal lowland belt, the significance of the area as an important dwelling place throughout the centuries cannot be ignored. Rice dominates life in Southeast Asia and is the staple food for the teeming millions in the crowded lowlands. The growing of the crop is largely limited to Southeast Asia to the tune of 95% of the present production (Braudel, 1977). For centuries the cultivation of wet-rice varieties has constituted the backbone of village economies on Java. Van Schaik (1986), states that 80% of the rice growing areas in Southeast Asia are presently confined to coastal lowlands and major river valleys. These coastal lowland areas and broad flat fluvial valleys resemble the original habitat of the wet-rice variety, which is in fact a cultivated grass originally found in swampy areas of Indochina. Being a swamp plant, rice is also the only cereal which can be grown on these originally swampy flat valleys and coastal lowlands.

Returning now to the coastal lowlands, it is interesting to contemplate the original virgin scenery of these northern coastal areas of Java. Van Schaik (1986, p:54), quotes a remarkable travel report of a British officer in 1813, who describes the first land connection between West and East Java as 'extremely narrow' in the lowlands of the present-day kabupaten of Brebes near the border with West Java. The lowlands were covered with swamps and jungles, hard to pass even on horseback. Based on this account it is not very likely that important wet-rice field cultivation had been established prior to the twentieth century. The major impeding factors are the high variability in discharge of the large rivers, leading to annual floods, and the drainage and reclamation of fresh water swamps on the flood plain; thus problems of flood control and drainage. From a geomorphological point of view, the most attractive areas for wet-rice cultivation on Java are:

1) Quaternary coastal lowlands, both in the north and to a lesser extent in the southern side of the island;
2) tectonic depressions in the central volcanic zone, such as found in West Java;
3) broad transverse valleys between the widely-spaced volcano cones in Central- and East Java, and the Bantul graben south of the town of Yogyakarta;
4) structurally-controlled strike valleys of the rivers Bengawan Solo, Kali Brantas and Kali Lusi, mainly in East Java.

Historically, wet-rice cultivation appears to have been developed initially on units 3 and 4 of the above list, thus in Central- and East Java (Geertz, 1963). This seems plausible on account of the smaller variability in discharge of rivers descending from young volcanic cones and carrying appreciable groundwater run-off in the dry seasons, the presence of large springs at the volcano toes and the favourable topographic gradient for drainage. Eventually, the increasing population must have led to expansion of wet-rice field cultivation onto the northern coastal lowland areas. Again from a geological point of view, the most favourable areas to start with wet-rice field cultivation in the coastal lowlands, irrigated by indigenous systems are:

1) flood basins near the smaller rivers which have their catchments in only the northern morphological belt;

2) fluvial dissected volcanic fans spread out in the coastal lowlands and dissected piedmont plains; these areas are safeguarded against flooding and possess favourable terrain gradients.

Geertz (1963, p:44), assumes that wet-rice cultivation in the northern coastal plain area (Pesisir) has in all probability been carried out 'particularly around the hundreds of minute estuaries which perforate the otherwise unvaried shore'. Estuaries along this deltaic coast are rather unlikely even for streams draining only the coastal plain. Tidal creeks exhibit an estuarine-shaped mouth but on geological grounds it is difficult to imagine how areas around tidal creeks, on high sulphate containing coastal swamp deposits and brackish near-shore deposits, could act as suitable areas for wet-rice cultivation.

Bakhoven (1936) describes the coastal lowlands in kabupaten Karawang at the turn of the century, prior to erection of the major western waterworks and irrigation channels, mentioning vast areas of marshy land. His maps show small areas and strips of wet-rice field cultivation adjacent to smaller rivers in the southern parts of the coastal lowlands, in fact on the piedmont plains and Late Pleistocene volcanic fans. The indigenous irrigation systems on Java existed only in favourable areas with dense populations (Van Schaik, 1986). These old Javanese systems consisted of a dam of stones, wood and bamboo in a river or brook upstream of the fields. The water was led by channel to the rice fields, where is was kept flowing slowly from one corner to the other, then to the next field and finally returned into the river or drainage channel. The disadvantage of this technology appeared to be the risk of damage to the small dams by floods (Bakhoven, 1936). Many parts of the coastal lowland were regularly flooded in the absence of a proper drainage system in the flood plain depressions between two larger rivers. It is generally accepted that with the implementation of the large irrigation schemes at the turn of the century under the colonial government (Braudel, 1977, Fischer, 1971 and Geertz, 1963), the technically irrigated rice field areas expanded significantly into the coastal lowlands (see Table 1.1).

Despite the problems of water control in the rainy season, which can be solved by appropriate technical waterworks, coastal lowlands are suitable for wet-rice field cultivation since even in the dry season supply and control of water is fairly easily achieved by impounding and diversion from natural channels. Many perennial rivers draining vast catchments in the mountainous hinterlands of Java traverse the northern coastal lowlands (see Fig. 1.3). On geological grounds the following factors can be mentioned as being favourable for wet-rice field cultivation:

1) many parts of the coastal lowlands consist predominantly of heavy soils of low-permeability montmorillonitic clays which high cation-exchange capacities;
2) salinity control of the soils by irrigation;
3) favourable suspended sediment loads carried by the natural streams;
4) favourable dwelling places on river levees, beach ridges and interfluves of dissected volcanic fans.

Favoured sites must have been the dissected Late Pleistocene volcanic fans spread by water action far into the lowlands, providing sites for wet-rice field cultivation in the newly incised valleys and flood free dwelling places on the higher terraces.

According to Geertz (1963) the supply and control of water, including the prevention of excessive flooding, is the key factor in wet-rice growing. Braudel (1977) attributes the

'Miracle of the aquatic rice fields' to the extraordinary high yields, by harvesting up to two or even three times a year with intensive utilization of the land. It is the circulation of the preferably muddy irrigation water, which is readily on hand in the northern coastal lowlands and to which even human- and animal excreta may be added, in the rice fields that continually supplies oxygen to the root systems and restores the soil fertility. The muddy irrigation waters also prevent settling of the malaria-carrying anopheles mosquito.

Table 1.1 Areas of irrigated rice fields in Kabupaten Karawang.

(Areas expressed in hectares)

Year	Technical	Semi-technical	Indigenous	Rain-fed
1900			7,800	9,200
1935	55,000	11,350		5,800

Source: areas in bahus (= 0.70695 ha) from Bakhoven (1936)

However, wet-rice cultivation in this suitable natural environment brought high populations and strict social discipline to the regions where they prospered. It also implied concentrations of villages because of collective requirements for irrigation control. Geertz (1963) emphasizes the special character of the rice field-ecosystem which can continue to produce, year after year, at a virtually undiminished yield. As long as a sufficient supply of irrigation water is at hand, even nutrients can be brought into the eco-system in case of low natural soil fertility. Although the population expansion was not accompanied by similar growth in rice field acreages, crop yields could be increased simply by intensification. As long as the eco-system could withstand a major breakdown, the process of applying more labour in rice cultivation could still raise the yields. This hypothesis of ever increasing paddy yields by higher inputs of labour has been criticized by White (1974), Van Schaik (1986) and many other scholars. Merely as an indication, present-day annual yields of paddy (threshed unmilled rice) in the northern coastal lowlands grown under fully technical irrigated conditions, averages 4,750 kg per ha (Sensus Pertanian Jawa Barat, 1983); unhusked rice loses 20 to 25% in weight leaving about 3,500 kg of rice ready for cooking. Van Schaik (1986) mentions paddy yields in the period 1860 to 1920 of about 1,700 to 2,600 kg per ha.

Being a triumph of peasantry closed in upon itself, rice cultivation was not directed towards the outer world. Conquest of the mountainous areas and the development of forestry and stock-raising was not even attempted according to Braudel (1977). The active populations were concentrated in the lowlands, in the broad river valleys and on the lower slopes of mountains. The uneven population distribution in Java is most conspicuous in West Java, with sparsely inhabited areas on the southern side of the island and the majority dwelling in the northern coastal belt. In Central Java this feature is less pronounced because of the extensive alluvial plains and coastal lowlands along the south coast (Fig. 1.2). Apart from geological factors and pedological conditions, the unevenly distributed population must be related to a certain extent to wet-rice agriculture. Notwithstanding the abundance of natural resources in the southern area, the lack of broad river valleys and broad coastal lowlands permitting intensive rice cultivation has discouraged inhabitation.

Data on population in Indonesia are based on national census results; population surveys covering the entire administrative area of Indonesia were held in 1961, 1971 and 1980. Table 1.2 shows the main result of these censuses for the kabupatens in the study area.

Table 1.2 Population densities in the study area, according to national censuses in 1961, 1971 and 1980.

Kabupaten Years	Area (km^2)	1961	Population 1971	1980	Densities (pers./km^2) 1961	1971	1980
Karawang	1,578	833,740	1,000,439	1,236,604	528	634	784
Subang	1,864	---	906,420	1,065,251		486	571
Indramayu	1,935	862,248	989,574	1,237,450	446	511	640
Cirebon	974	1,062,413	1,222,420	1,555,194	1,091	1,255	1,597
Brebes	1,658	894,671	1,051,672	1,263,988	540	634	762
Tegal	902	853,301	980,463	1,231,377	946	1,087	1,365
Average :						768	953
Total :			6,150,988	7,589,864			

Source : Biro Pusat Statistik Jakarta 1963, 1973, 1981.

Population data for kabupaten Subang are not available for the initial census in 1961. High population densities are found in the kabupatens Tegal, Cirebon and to a lesser extent in Karawang and Brebes. Subang and Indramayu are relatively sparsely populated, even compared with the average density of 635 persons per km^2 for the entire province of West Java, excluding the Jakarta area. The highest densities are found in kabupatens with the smallest areas, such as Cirebon and Tegal.

In Fig. 1.4 population densities are plotted versus the census years. A remarkable difference exists between the 'high-density' kabupatens Tegal and Cirebon and the 'low-density' kabupatens Brebes, Subang and Indramayu, also expressed in the rates of density increase. The three latter kabupatens have a principally rural population, whereas in Cirebon and Tegal important urbanization has taken place. Both harbour towns Tegal and Cirebon are registered in all the national census statistics as municipalities. According to the National Urban Development Strategy Project NUDS (1985), growth rates in urban centres range between 4 and 5%. These are much higher than rural growth rates of 1.5% to 1.7% as estimated by IWACO/WASECO (1987a).

The Regional Development Project West Java LTA-47 (1986), indicates that the agricultural sector absorbs little extra labour and many people migrate to urban areas. Movements from rural to urban centres within provinces are the most important source of migration for all areas. The study concludes that while net migration is negligible, 98% of the total population growth in the province of West Java is attributable to urban population growth. The National Urban Development Strategy Project NUDS (1985) summarizes its main findings on the patterns of population growth for Java as follows:

1) growth within a province is seldom uniform;
2) kabupatens surrounding the largest cities show the highest growth;
3) high-growth areas are almost always found along the coasts and in particular the coast along the Java Sea.

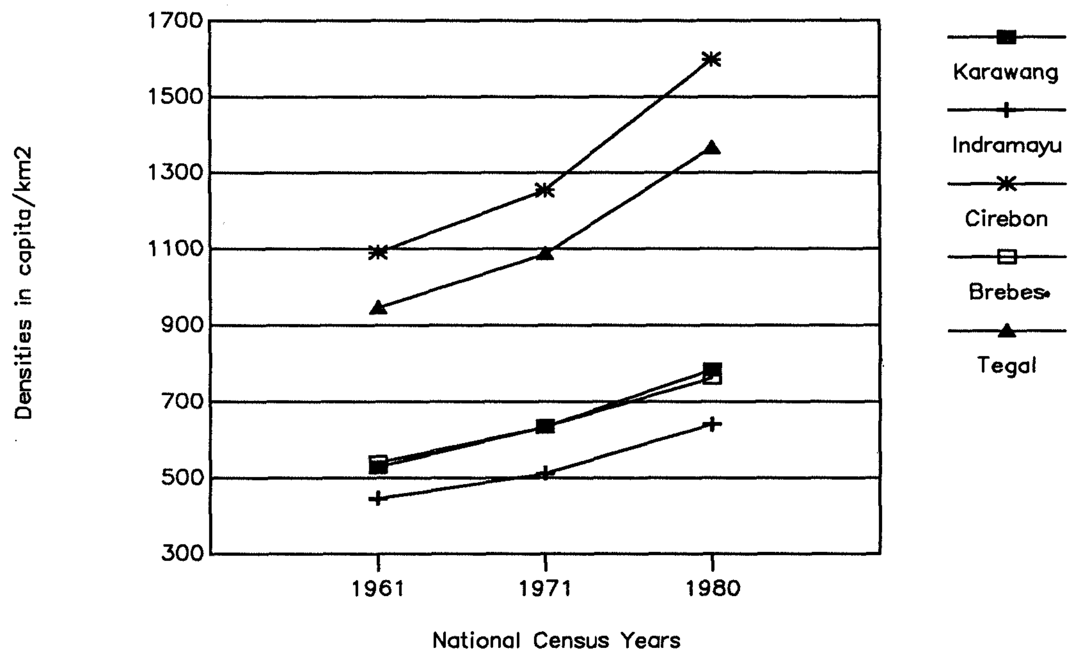


Fig. 1.4 Population densities according to the 1961, 1971 and 1980 national censuses.

1.3.2 Water supply and salinization

Contrary to the favourable hydrological aspects of the coastal lowland as a natural environment for wet-rice cultivation, the groundwater hydrological setting is posing serious difficulties with respect to the supply of safe domestic water. Vast areas in the coastal lowland are characterized by saline shallow groundwaters which are mostly unfit (according to WHO standards) for human consumption. These saline shallow groundwaters are not necessarily arrayed in belts along the present coastline, but can also occur in zones along the southern boundary of the coastal lowlands tens of kilometres from the present shoreline and at elevations far above mean sea level; fairly highly mineralized shallow groundwaters (TDS up to several grams per litre) have been identified.

Most of the older villages were built near river channels, abandoned channel sands or on elevated beach ridges, thus in general near fresh water sources and on a stable subsoil. The ever increasing population densities created by rice field-ecosystems and immigration towards the coastal lowland kabupatens, caused the newer villages to gravitate towards less favourable parts of the coastal lowland.

In the present-day setting, irrigation water from the dense network of canals provides an alternative source of domestic water supply in case of saline groundwaters. These open irrigation canals are obviously vulnerable to pollution by pesticides washed from the rice fields, human excreta and solid waste disposal in the absence of proper sewerage systems. A distinction has to be made between water for human consumption and that for washing purposes. Brackish shallow groundwaters may still be utilized for washing purposes. The situation is frequently encountered in which a particular dug well producing relatively low salinity water is reserved for drinking water, whilst the remaining dug wells serve the purposes of washing and bathing.

During the colonial period, a programme was started in the beginning of this century to sink deep wells in the coastal lowland areas to meet the demand of safe water. Initially self-flowing for decades, the majority of these old wells now have to be pumped. From the 1970s onwards, numerous small diameter deep wells were drilled by the local inhabitants in an effort to alleviate the problematic water supply situation. However, the situation found for the shallow groundwaters applies also to the deeper groundwaters. At first glance fresh and saline groundwaters are chaotically distributed in both a vertical and horizontal sense, even at some distance from the present-day coast. Vast areas occur with highly saline groundwater along the entire depth of tube wells drilled by low-technology jetting methods.

Many old colonial wells, producing good water for decades, show gradual increases in salinities which are apparently unrelated to regional salinization or invading seawater fronts. Conversely, deep wells sunk to the same depths but closer to the Java Sea may yield water under artesian pressure with significantly lower dissolved solids. During the colonial days deep wells have also been sunk in a number of small coral reef islands (Onrust, Edam and Kuiper, presently known as Pulau Kapal, Pulau Cipir and Pulau Damar Besar) in the bay of Jakarta, yielding fresh to brackish which can be under artesian pressure.

1.4 Previous research in the northern coastal lowlands of Java

In 1843 the first deep water well was drilled in Batavia (presently Jakarta) at Fort Prins Hendrik (Purbo-Hadiwidjoyo, 1977). At the end of the 19th century a programme of deep water well drilling was initiated under the Netherlands colonial government, with peak activity in the beginning of this century. Notwithstanding the publication of drilling data in annual reports such as the 'Jaarboek van het Mijnwezen', extensive hydrological investigations into the groundwater resources of the coastal lowland belt had not been carried out. In his famous book *The Geology of Indonesia*, Van Bemmelen (1949) casually mentions the 'lowland plain of Batavia' and describes it as alluvial and often marshy land, built up by the silt load of rivers debouching into the shallow Java Sea considered then to be a submerged peneplain.

The Geological Survey of Indonesia published the first tentative groundwater map of Java and Madura in 1960, compiled by Purbo-Hadiwidjoyo. Recently, in 1985, hydrogeological maps were published by the Indonesian Directorate of Environmental Geology, Bandung at a scale of 1:250,000. The groundwater mapping was carried out in the framework of a cooperation with the West German Hydrogeological Advisory Group (CTA-40). The sheets II (Cirebon) and VI (Pekalongan) cover major parts of the northern coastal lowland, and were compiled by respectively Soetrisno S. (1985) and A. Tabrani Effendi (1985). According to these maps, the northern coastal lowland is underlain by aquifers with an intergranular type of groundwater flow. Three types of aquifer productivity are distinguished, that is to say moderately productive aquifers with well yields of less than 5 l/s, extensive productive aquifers with individual well yields ranging from 5 to 10 l/s and highly productive aquifers with more than 10 l/s per well. Geologically the Quaternary sediments are described as alluvial deposits consisting of sands, gravels, clays and silts. Saline groundwaters are thought to be the result of both salt water encroachment and contamination by connate sea water. Apart from a boundary indicating the limit of artesian flow, the maps do not reveal any hydrological information on the deeper aquifer systems in the coastal lowland.

Due to heavily urbanized centres in the coastal lowland belt and their related environmental problems, research from an earth-scientific point of view has increased rapidly since the 1970s. The ever deteriorating well water qualities and dropping artesian heads in the course of time have urged Indonesian governmental institutes such as the Geological Survey of Indonesia (GSI) and Public Works (PU) to carry out groundwater investigations, mostly in cooperation with foreign consultant firms. Most of these unpublished reports stress the complex hydrogeological situation in the coastal lowland belt of randomly distributed thin sandy layers embedded in mainly clay layers. Mechanisms of sea water intrusion are usually invoked to explain deteriorating groundwater qualities. However, Meinardi (1976, 1977) concludes that not all the inland saline groundwaters may be attributed to sea water intrusions, but may also originate from saline connate waters. In groundwater studies of the villages of Krangkeng and Totoran (kabupaten Indramayu, West Java), Meinardi (1976) argues that evapotranspiration losses from the almost stagnant shallow groundwaters in the flat deltaic plains leads to increasing dissolved solids in the absence of proper salt leaching.

Hehanussa & Hehuwat (1979) report on the morphogenesis of the northern coastal lowland in West Java, in which they stress that the interaction between riverine and marine systems has led to a net progradation of the coast. Coastal lowland development is controlled by the main fluvial systems in the area. Superimposed on these fluvial processes are the effects of eustatic sea level fluctuations and Quaternary tectonic movements in the underlying Plio-Pleistocene basement. The thickness of strata in the Quaternary basin in Jakarta exceeds 250 m and may reach 300 m locally. Both authors attribute a belt of saline shallow groundwater adjacent to the coastline to saltwater intrusion. The same salinization mechanism of saltwater encroachment is thought to also affect the deeper groundwaters (Hehanussa, 1979). The same author emphasizes the inland seawater incursions into the channel of the river Cimanuk in Indramayu of up to 7 km in the dry season, and that a wide area around the river has been affected by seawater.

Soekardi & Koesmono (1973) distinguish nine lithologic units in the Jakarta area based on key beds, marine fossils and groundwater conditions. Three main sediment groups are mentioned:

1) marine sediments built up of greenish to bluish grey clays, quartz sands, black sands and mica rich sands, all associated with fossil fragments;
2) fluvial sediments consisting of clays, often carbonaceous, up to conglomerates;
3) volcanogenic sediments.

Soekardi & Purbo-Hadiwidjoyo (1979) divide the Jakarta groundwater basin into four aquifer systems: system A up to 60 m depth, system B from 60 to 150 m, system C from 150 to 225 m and system D at depths greater than 225 m. All these authors are confident concerning the salinization mechanisms, which is thought to emanate from seawater invasions.

Binnie and Partners (1982) conducted a programme of exploration drilling in the coastal lowland in the Kabupatens Brebes, Tegal and Pemalang to appraise the groundwater resources in terms of irrigation potential. After re-examining old bore hole descriptions of wells drilled prior to 1940, the consultants conclude that clays are predominant and alternate with sands and silty sands, with an occasional thin gravel layer. The percentage of sand occurring in the upper 150 m of the Quaternary deposits is generally in the range of 6 to 30% and the number of sand layers between 1 and 10. Thicknesses of the sand layers are very variable and are believed to be of very limited horizontal extent. The consultants further stress the absence of any apparent lateral correlation between adjacent bore holes. A remarkable conclusion is drawn by Binnie and Partners concerning the vertical extent of the Holocene/Late Pleistocene deposits, based on a GSI bore hole (No. 498) in the Pekalongan area. They arrive at a thickness of at least 394 m. The hydrostratigraphy is thought to consist of a shallow unconfined aquifer at depths less than 60 m and a confined aquifer at depths of more than 70 m. The latter aquifer exhibits steadily increasing hydraulic head with increasing depth. The consultants report highly varying transmissivity values ranging from 50 to 400 m^2/day.

In his explanatory note to the hydrogeological map of Indonesia, sheet II Cirebon (West Java), Soetrisno (1985) remarks that the northern coastal lowland is mostly formed by unconsolidated materials. Mainly clay layers are present with some thin sand layers and at great depths, shales. The deltaic sedimentary environment is responsible for the almost random distribution, both vertically and horizontally, of pervious and practically impervious layers. Three main processes are advanced to explain salinization of the coastal lowland groundwaters, both shallow and deep-seated, namely seawater encroachment, connate waters and inland salinization.

Pramono (1981) distinguishes three aquifer systems, i.e. an upper system at depths less than 60 m, a middle system from 60 to 100 m and a lower system. The middle system is valued as being the most productive. He further notes that fresh deep confined groundwater may not be present in all parts of the coastal lowland, since some deep drillings failed to encounter any fresh groundwater bearing layers.

The field investigations for the presented study, covering the northern coastal plain areas in West and Central Java, were initiated during the execution of a bilateral Indonesian-Netherlands development project. This development project, registered by the Netherlands General Directorate for International Cooperation (DGIS) under the code OTA-33/J7, started in 1976 and was aimed at improvement of the rural domestic water supply situation in selected regions of West Java. The head office of the project was based in Bandung, West Java. It was incorporated into the organizational framework of the Indonesian Department for Health and Sanitation (DepKes). This department is responsible for the health and sanitation aspects of domestic water supply at rural levels. The Netherlands 'International Consultants for Water and Environment IWACO B.V.' (abbreviated as IWACO), with head office in Rotterdam, was appointed by the Netherlands government to act as counterpart in the OTA-33 project.

Among various other project activities, a survey programme was conducted to determine locations for 18 deep wells in the northern coastal plain of West Java. It was during these surveys, at the beginning of the project, that IWACO hydrologists became aware of the complex groundwater situation in the area. At that time the available hydrogeological data at the Geological Survey of Indonesia (GSI), based in Bandung, proved to be fairly meager and patchy and dated mainly from the pre-war period. This incompleteness of basic hydrological data at GSI with respect to coastal lowland areas, severely hampered the integrated regional planning of rural water supply demanded by the project.

For logistical reasons the Indonesian Geological Survey could not become involved directly in the hydrogeological surveys of OTA-33. Hence, plans were conceived in 1979 by DepKes and IWACO to provisionally extend the project activities with systematic water resources investigations. For reasons of logistics and masterplanning, the investigation efforts were focused at kabupaten level.

At a later stage in the OTA-33 project, the National Institute for Geology and Mining (LGPN) of the Indonesian Institute for Sciences and Research (LIPI) became informally engaged in the water resources investigations, because of coincident survey areas and interests. It was mutually decided to give this ad hoc survey cooperation formal status by submitting a project proposal to the Netherlands General Directorate for International Cooperation (DGIS), after the proposed project 'Groundwater surveys in the northern coastal plain of West Java' had been registered by the Indonesian National Planning Board (BaPeNas) under the code TTA-96. However, the ceiling on DGIS development funds in 1981 eventually prevented execution of the proposed project. Meanwhile, the OTA-33/LIPI work continued intermittently until mid-1984, finalizing the surveys of four kabupatens. The results of these survey activities were laid down in four unpublished OTA-33/LIPI reports.

After a period of two years the survey activities in the coastal plain were resumed (in 1986) during execution of the 'Earth Sciences Project, phase 3', in the framework of the Netherlands-Indonesian Inter University Programme of Cooperation.

1.5 Organizational framework

Research activities were finally consolidated during execution of the Earth Sciences Project Phase 3, 1985-1988 (ESP-3), in the framework of the Netherlands-Indonesian Inter University Programme of Cooperation. This project consists of a cooperation between the Universitas Gadjah Mada (UGM) at Yogyakarta, Central Java, and the Free University (FUA) of Amsterdam (The Netherlands) in conjunction with the International Institute for Aerospace Surveys and Earth Sciences (ITC) at Enschede, the Netherlands. The project is sponsored by NUFFIC, i.e. the Netherlands University Foundation for International Cooperation. The executing institutions comprise the Faculty of Geography of the UGM and the FUA Institute of Earth Sciences.

Principal aims of the Earth Sciences Project, Phase 3 are the initiation of research and guidance for various components of the Physical and Technical Geography research programmes. Part of the research is focused on typical problems of land and water resources development planning along coasts and coastal lowlands, in liaison with various Indonesian governmental institutions at local and national level.

Since the present author had already surveyed four kabupatens in West Java, the survey activities shifted to the northern coastal lowland areas of Central Java, where Indonesian students from the UGM Faculty of Geography and Netherlands students from the Free University of Amsterdam carried out initial field investigations. With regional surveys targeting Central Java, more detailed surveys were performed in the kabupatens of West Java.

A further cooperation was established with the Netherlands International Consultants for Water and Environment IWACO to exchange information concerning survey activities and to provide opportunities for Indonesian students to carry out field investigations under their guidance. IWACO initiated a similar project in West Java (Groundwater Resources Survey in West Java), financed by DGIS, in cooperation with the Directorate General of Human Settlements (Cipta Karya) under the Indonesian Ministry of Public Works.

II. METHODOLOGY

2.1 Earth and water systems approach

2.1.1 Introduction

The concept of a 'system' and the consistent approach of identifying systems and their mutual relationships is a relatively new development in the field of earth sciences. System analysis in earth sciences is aimed at understanding the complexity of interwoven and interrelated processes as found in nature. These may range between two extremes, that is to say from entirely man-made processes to ones still undisturbed by man. System analysis attempts to identify the interrelated single elements and entities that constitute the whole physical framework under investigation, in space and time, form, structure and the cause-and-effect relations. Engelen and Jones (1986) give an elaborated summary on the concept of a system and its historical development in earth sciences in the last decades.

2.1.2 System concept in hydrology and historical development

The definition of a system varies widely between scientific disciplines, from a region of space as part of the universe temporarily marked off for discussion to interdependent groups of items, both in a material and in abstract sense forming a unified whole, up to orderly arrangements and classifications. The main underlying principle, however, emphasizes the orderly assemblage of objects or items in a real or abstract sense. In hydrological sciences, Dooge (1973) advances the definition of a natural hydrologic system as 'a structure device, scheme or procedure, real or abstract, that interrelates in a given time reference, an input, cause, or stimulus of matter, energy or information and output, effect, or response of information, energy or matter'. His definition is clearly intended to describe the relationship between components of the hydrological cycle. Concerning groundwater hydrology, Domenico (1972) introduces and defines the concept of a system in groundwater hydrology as incorporating fields of science, engineering and management. He argues that these three disciplines are engaged in groundwater systems, since science should investigate the physical phenomena, engineering the practical achievements and management the control of a particular situation. In general, systems analysis in groundwater hydrology attempts to investigate the entire physical framework in which groundwater occurs, be it flowing or stagnant, up to its natural or artificial boundaries.

A major advance to the concept of groundwater systems was achieved in the early 1960s by Toth (1962, 1963) with his mathematical model representation of a two-dimensional regional groundwater flow system in a small drainage basin. Toth arrives at an analytical expression for the Laplace equation for a vertical rectangular flow domain with impermeable boundaries, which is thought to simulate groundwater flow between a drainage divide and a stream in a valley bottom (see Fig. 2.1). The upper boundary of the model consists of a linearly increasing fixed head boundary to simulate a gentle sloping water table. In a later development, Toth (1963) superimposed a sinusoidal function on the linearly increasing fixed head boundary to simulate a gently rolling water table following the topography. This model demonstrates the existence of local, intermediate and regional flow systems which are clearly separated into flow domains connecting recharge with discharge areas. The local flow systems are nested within the intermediate systems and the latter in turn within the regional flow system.

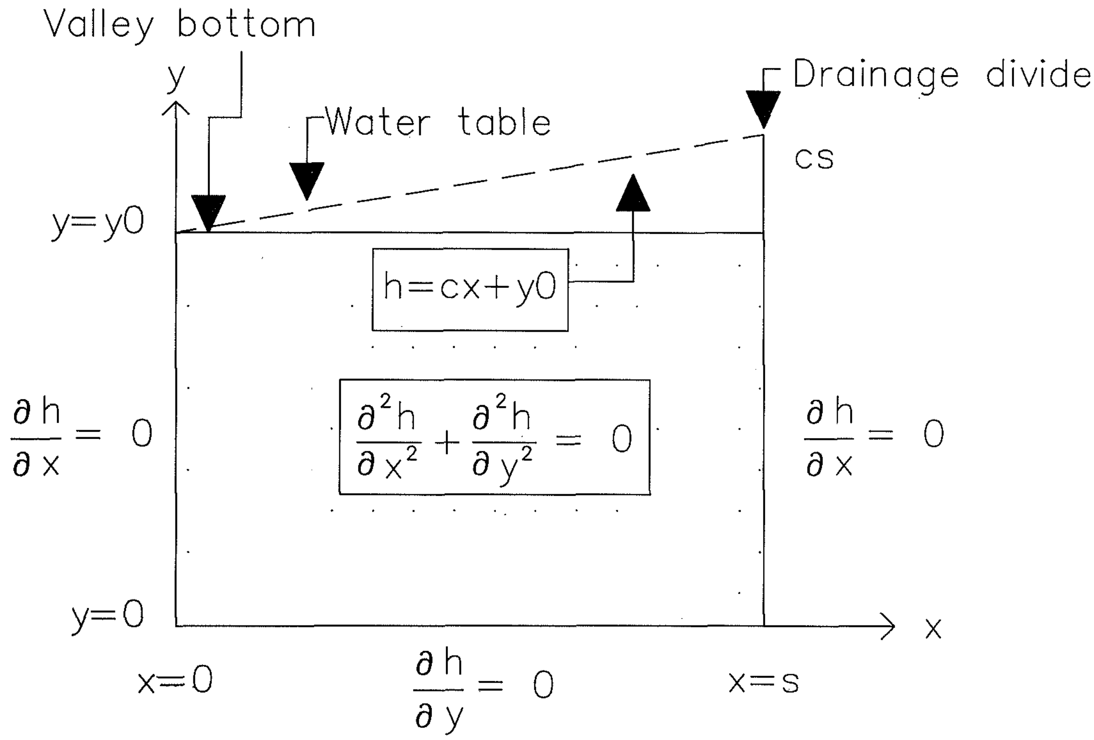


Fig. 2.1 Toth's (1962) vertical model for groundwater flow.

Toth demonstrates that a study of a regional groundwater system should not be confined merely to the aquifer itself, but encompass the entire groundwater flow system which may occupy several aquifers or only a part of a particular aquifer.

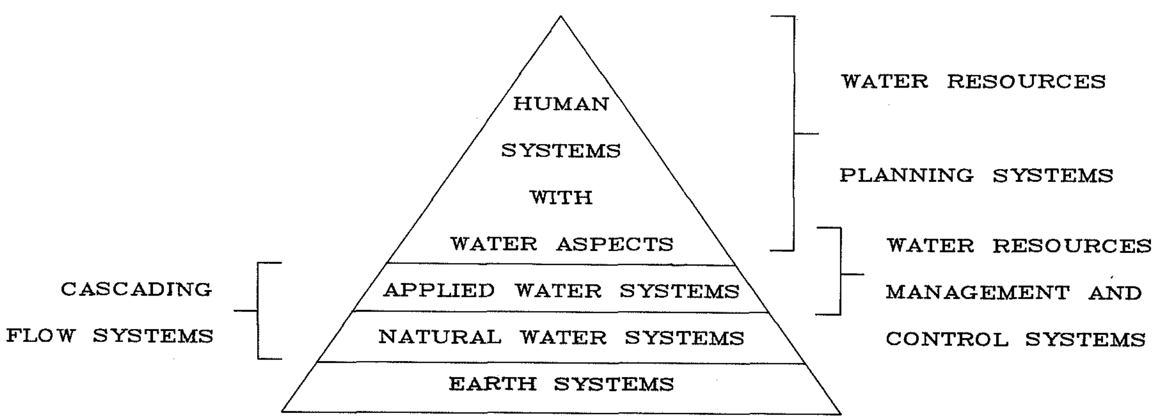


Fig. 2.2 Hierarchy of water related systems, according to Engelen (1986).

It is the groundwater flow system which emerges as the basic unit from his models rather than the aquifer.

The concept of hierarchically-nested groundwater flow systems introduced by Toth has been extended and developed further by Engelen (1980, 1984). Engelen demonstrates that hierarchically-nested groundwater flow systems exist in widely varying topographical, climatological and geological settings. According to Engelen, systems are created and developed through time and space, during which they pass through various stages before they finally vanish. A variety of parameters are involved to describe and delineate earth and water systems, such as boundary types, shape, input and output, system flux and hierarchical position. A general hierarchy of water related systems is proposed by Engelen (1986) and depicted in Fig. 2.2.

2.1.3 *Hierarchy and mutual relations in water and earth systems*

In any orderly assemblage of modules or entities with mutual input/output relations a structure of organization will emerge. The arrangement of modules or entities will reveal ranks and order, in which entities of a similar rank are subordinate to those of higher rank. Thus a hierarchy of systems might then be noticeable which controls flow directions of energy, matter or information. The inter-system transfer of energy, matter and information may take place spontaneously or after exceeding certain threshold values. Systems of similar rank may be divided further into subsystems according to a particular hierarchy. At the level of similar rank, systems are characterized by a certain degree of equivalence in scale, responses, phenomena etc. They may be separated from each other within one level or being placed side by side, incorporating inter-system transfers. System boundaries may shift back-and-forth without being detrimental to the hierarchical structure.

The point of observation and the zooming effect in the study of a particular framework of systems can be crucial in understanding the structure and hierarchy. Focused to a subsystem, one may gain insight into the hierarchy within that specific level without comprehending the mutual relation with systems in the same or other levels. An apparent chaotic assemblage of systems may reveal a consistent hierarchy when viewed from a lower magnitude of zooming. The biologist Dawkins (1988) calls it 'hierarchical reductionism', which 'explains a complex entity at any particular level in the hierarchy of organization, in terms of entities only one level down the hierarchy; entities which themselves are likely to be complex enough to need further reducing to their own component parts; and so on'.

In the study of groundwater systems in the coastal lowlands of North Java it is attempted to pursue the 'system approach' in the widest sense. The complex earth systems on the island of Java play a role of paramount importance in the shape and development of the embedded overlying natural water systems. In particular in this part of the globe with active plate tectonics, the processes in the upper mantle of the earth strongly influence the conditions at the surface in a way which is manifold. The relatively simple convection currents in the mantle in which hot and perhaps partly molten rocks are involved have profound cause-and-result effects at the earth surface. Processes in the upper mantle systems trigger a chain of reactions with a certain time lag in the overlying crustal systems and consequently the effects may even be noticed in the natural water systems. Fig. 2.3 depicts the various earth and water systems with the relationships of cause-and-effect.

From the upper mantle an upward direction of influence is discernible up to the natural water systems. The energy output of the upper mantle systems is transferred to the overlying crustal systems in a cascade-like manner. Energy is converted and diversified giving rise to the triggering or activation of a wide variety of crustal systems, or even the creation of new systems. From the opposite direction, human control systems exert influence on the applied systems which have their effects on the natural water systems. The natural water systems are situated at the centre of two converging domains of influence.

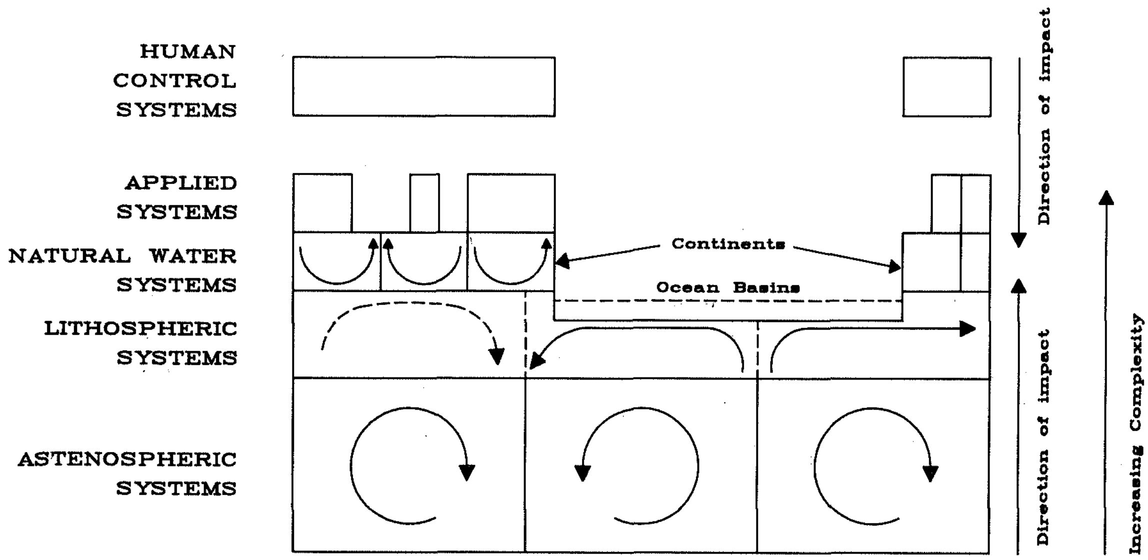


Fig. 2.3 Major earth and water systems.

Table 2.1 Earth and water systems and major subsystems.

Astenosphere :	Convection cells with scales up to thousands of kilometres;
Lithosphere :	Plate tectonic systems, possibly driven by the convection systems in the astenosphere : Subduction belts; Sea-floor spreading zones; Transform fault systems; Magma generating systems; Isostatic compensation systems; Tectonic systems; Erosion-, transport-, accumulation- (ETA) systems;
Natural water :	Atmospheric systems; Surface water systems; Groundwater systems.

For the sake of completeness, (extra)-terrestrial impacts and influences active during geological periods should be mentioned, since they may alter conditions in the earth's atmosphere and consequently influence the crustal- and natural water systems. The lag times between impact and system response are measured against a geological scale for the upper mantle/crustal systems, whilst for human impacts on natural water systems the response may be felt after decades or even years. The energy impulses, propagation, dissipation and final responses follow the paths of the system hierarchy.

The natural water systems are embedded in the crustal systems and the crustal systems are in turn embedded in the upper mantle. Moving upwards in Fig. 2.3, the diversity and complexity of systems is seen to increase dramatically. The major systems are listed in general outline in Table 2.1.

2.2 *System approach in the present study*

2.2.1 *General system framework*

The scantiness and doubtful quality of available geological and hydrological data of boreholes in the coastal lowlands in North Java hampers the study of the behaviour and characteristics of the groundwater systems. Assuming even the presence of a wealth of hydrogeological data, one may still be faced with a range of puzzling phenomena which makes it hard to comprehend the groundwater systems, their mutual relations and driving mechanisms.

As seen from a systems approach, the hydrogeological complexity of the coastal lowlands cannot be fathomed merely by investigating the present groundwater systems. The lowland groundwater systems should be seen in the wider context of a geological framework. Geological developments in the coastal lowlands are largely controlled by the geology and structures of the hinterland. The present coastal lowlands, or more generally the Quaternary filling of the sedimentary marginal basins, are strongly linked to the regional developments of magmatic arc building during the Pleistocene epoch. The major volcanic outbursts on a regional scale in Middle- and Late Pleistocene times have furnished considerable sedimentary fill material for the marginal basins. Hence, development of the Quaternary marginal basins cannot be seen separately from developments in the volcanic arc of Java. In order to comprehend the patterns and belts of Pleistocene volcanism, another system at a larger scale, viz. the entire geological and tectonic framework of Java, should be considered. The chain of cause-and-effect processes, which resulted in the building of the coastal lowlands, must be followed from the higher rank of the major energy producing system of plate subduction. Thus in the terminology of system analysis, the earth and water systems should be traced following the path from higher to lower system hierarchies. The geological developments are traced by following a tree structure of scale and time. With each step the branches are descended and objects are being studied at reduced scales in time and space.

Important geological processes during the Pleistocene epoch inevitably must have left their imprints on the sediments in the coastal lowlands. By utilizing drilling data only, one may easily neglect specific lithological features which are of paramount importance in reconstructing the depositional environment. It can be reasoned that certain geological processes or events during the Quaternary period must have left their imprints even on rocks in the Tertiary terrains bordering the coastal lowlands on the southern side. This is the aspect of inheritance, implying that objects at a certain rank in the hierarchy of time and space may have inherited characteristics from objects at higher levels in the hierarchical structure. Thus the depositional history and conditions which prevailed in the Quaternary basins might be inferred from specific geological features present as overprints in the Tertiary rocks. This approach of unravelling marginal basin developments by looking at geological features in the hinterlands has been followed in the present study, by carrying out detailed field surveys in the Tertiary terrains on the southern border of the coastal lowlands. In particular, tectonic features, planation surfaces, rudaceous relict deposits and fossil soil horizons have been surveyed in outcropping Tertiary rocks.

2.2.2 *Aspects of time and scale*

The present study attempts to encompass the frameworks of both geological time and scale. The framework of geological time relevant to Quaternary coastal lowlands development dates back as far as early Tertiary times, during which the major plate subduction systems of present-day Java were presumably established. Hence it appears that the maximum scale of the geological framework coincides most logically with a consuming plate boundary model, as it can be expected that a volcanically active island arc has come into existence from early Tertiary times onwards. A plate boundary model is a well-defined element in the plate tectonics hypothesis and its tectonic setting and surface manifestations are well-known today. The plate tectonics hypothesis imposes tight constraints on interpretations made within its framework. A conspicuous feature of such plate tectonic models is the more or less analogous patterns of development and evolution between entirely different geographical areas. A typical sequence of tectonic phases of uplift, normal faulting, magmatism etc. are easily recognized in similar settings of consuming plate boundaries. Knowledge gained in similar plate tectonics settings but other parts of the world may be applied to explain typical features in similar settings. Another argument is the strong interrelationship of processes and developments along subduction zones on the one hand and the activities along global mid-oceanic spreading centres on the other. As will become apparent in subsequent sections, reorganizations of remote oceanic spreading centres may strongly influence sedimentation patterns at consuming plate boundaries. With the present knowledge on these magmatic island arc-trench settings, the geological evolution, sediment patterns and basin development throughout the arcs are better understood. Literature on the subject of plate tectonic models advocates the relevance of considering the entire system in terms of geological time and scale (Cloetingh 1986, Wortel 1986).

The Quaternary sedimentary basins along the northern coast of Java fit well into this framework of a consuming plate boundary model as the continental back-arc basins, since they are underlain by a semi-continental crust. A complex mosaic of basins and highs has been developed in the Java back-arc areas since Miocene times, caused by oceanic plate subduction processes and crustal stress patterns. Le Pichon et al. (1976) give a range of 500 to 700 km behind the consuming plate boundary, depending on the dip and length of the sinking oceanic plate, as the zone of lithosphere which is still affected in its evolution by plate underthrusting processes along the trench. Patterns of sedimentation in the former

Tertiary back-arc areas, which after uplift were converted into the sediment provenance areas for the Quaternary basins, must have had their effects on the deposits in these latter basins.

Table 2.2 Time and scale of various phenomena in the study area.

	Moment	Chron	Age	Epoch	Period
Lithospheric plates				Plate reorganization	Plate subduction; Oceanic ridge systems
Plate sector/ segment		Tropical wet-dry planation building; Wet tropical rejuvenation;	Climatic fluctuations; Ascending magma diapirs	Emergence of volcanic arcs;	Magma generation;
Region	Volcanic ash + lapilli showers;	Volcanism; Marine clay blankets; Branches of deeper groundwater flow Sea level fluctuations; Prograding lowland coasts;	Climatic zoning; Gravity tectonics; Uplifts; Geanticlinal collapse	Changes in intraplate stresses	Sedimentary basin filling;
Sub-region	Volcano eruption; Land subsidence; Floodplain sedimentation; Prograding deltas;	Creation of groundwater sys- systems; Aquifer flushing; Soil formation; Volcano collapse; Gravity tectonics;			
Locality	Group of wells; Landslide; Shallow groundwater flow; Delta distribution channels;	Soil formation; Tropical river incision Planation dissection;			
Site	Outcrop; Well drawdown; Perched groundwater;				

In a recent study Cloetingh (1986) gives strong support for the idea of the effect of intraplate stresses on basin stratigraphy, in particular along passive plate margins. This author notes the remarkable correspondence between tectonic events, associated intraplate stress changes and rapid changes in apparent sea level or vertical motions of the lithosphere at basin flanks and plate interiors in passive margin settings. He further points out that changes in plate stresses and apparent sea levels may also hold for a wider range of settings, including subduction zones. All these aspects of consuming plate boundary models indicate that each element in the model is governed finally by the principal driving mechanism of oceanic plate underthrusting.

The reasoning of considering coastal lowland development in a broad perspective of scale and time can be reversed by departing from the present-day configurations, characteristics and zoning. The majority of these present-day features are not easily explained without contemplating the previous geological development, placed in a broader context. The three geological time spans, i.e. Tertiary, Pleistocene and Holocene, each had its specific influence on regional degradational and depositional patterns, geological structures and groundwater formation. Geological time spans and scales can be subdivided into units to serve the purpose of classifying geological processes, features and events in a matrix of scale and time.

Table 2.2 shows a framework of scale and geological time upon which major processes relevant to the area are projected. The lithospheric plates extend for thousands of kilometres, whilst the plate sector/segment at a lower rank has dimensions in the range of hundreds of kilometres. A plate sector/segment may refer to a plate segment or plate margin. A region may coincide for example with major parts of the coastal lowlands or a geological province, extending beyond large catchment divides or administrative kabupaten boundaries. Subregions have sizes in the order of kilometres, like smaller drainage basins in the Tertiary hinterland. Localities can be measured from tens to a few hundred metres. The geochronological divisions of period and epoch cover time spans such as Tertiary and Pleistocene, respectively. Ages stand for subdivisions of an epoch such as Upper Pleistocene and chrons may coincide with glacials and interglacials. A single layer of volcanic ejectamenta can be deposited during a geochronological moment.

The table exhibits a diagonal, from processes active on a small scale and short time span in the lower left vertex of the diagram, to mega-scale processes during considerable geological time spans in the upper right diagram vertex. In general, the smaller the scale and active time span of the earth systems, the lesser becomes the detectible effect.

2.3 *Scientific framework*

The present study deals with the identification of groundwater systems in the larger part of the northern coastal lowlands of West and Central Java in relation to the geology and morphology of the hinterland and major geological events during the Quaternary period. As a general guideline, the hierarchy of earth and water systems is followed in order to explain the present-day phenomena in the coastal lowlands.

Starting from the overall framework of a consuming plate boundary model which constitutes the highest level of hierarchy, the major geological events are traced in duration and discernible effects towards lower levels of hierarchy. By descending to lower levels of hierarchy, both time and scale will be reduced in magnitude, but the number of subsystems will increase. Thus starting from the overall framework with relevant magnitudes of geological time and scale, attention is then focused on subsystems or subframes at lower ranks. Starting from the major events in the Tertiary, the geological events in the Quaternary will be explored, up to developments in the Holocene which might have controlled or influenced sedimentation and groundwater formation in the Quaternary basins. With reference to Table 2.2, the diagram diagonal is more or less traced from processes at mega-scale and geochronological periods to small scale processes with durations of geochronological moments.

Systematic earth-scientific research of the northern coastal zone of Java (geology, tectonics, morphology, climatology and pedology) has yet to be published. Existing major studies of the coastal lowland groundwater hydrology are mainly concerned with water production aspects by various types of wells and groundwater availability maps. Groundwater types are distinguished merely on their chloride contents and only the classical fresh water-salt water interface models are invoked to explain groundwater distributions. However, the complex phenomena encountered in the studied coastal lowlands are not easily explained by these classical concepts and models of coastal hydrology based on differences in specific densities between fresh and salt water. Groundwater flow analysis is usually pitched to the level of analytical and numerical models at a time scale of only geochronological moments, without considering developments and evolution in groundwater systems.

In the present study an earth-scientific approach is pursued. Extensive field surveys have not been limited to the coastal lowlands, but also extended to the adjacent Tertiary terrains in the hilly areas to investigate features of lithology, stratigraphy, tectonics, pedology and morphology. It is reasoned that the geological history of the Quaternary basins could be reflected, albeit fragmentarily, as secondary features and overprints in the Tertiary terrains of the hinterland. Efforts are made to discern tectonic patterns and zoning transverse to the general structural trend, at the scale of lithospheric plates and plate margins, which may control the configuration of the Quaternary basins. The conspicuous shoreline of Java with protruding headlands and bays, and the configuration of the coastal lowlands suggests a certain structural control.

Special attention is paid to the surmised effects of Quaternary climatic fluctuations on the depositional environments. Verstappen (1974, 1980) advances the hypothesis that the Inter Tropical Convergence Zone (ITC) may have shifted significantly during the Quaternary glacials/interglacials resulting in regional climatic fluctuations. Smit Sibinga (1949, 1951 and 1953) stresses the importance of Quaternary eustatic sea level fluctuations on Pleistocene stratigraphy and morphology and attempts to correlate morphological remnant features in Java, Kalimantan (Borneo) and Sumatra with major European glacials; however, without contemplating the effects of climatic change. This author notices the widespread occurrence of 'black soils' (1949, p:13) in Pleistocene strata and makes a passing reference to the particularly dry monsoon conditions necessary to develop such soil types. Hitherto, none of the published groundwater studies of the coastal lowlands, except for Kloosterman (1986), consider sedimentary environmental conditions in the Quaternary basins in relation to climatic conditions. Concepts of transgression and regression in invariable humid tropical climates are invoked as the sole mechanisms which controlled depositional environments.

The hilly Tertiary areas with frequently occurring planation levels have been searched further for geomorphological and pedological evidence with respect to important climatic changes during the Quaternary. A number of different scholars have pointed out, in recent years, the drastic effects of climatic changes on the geomorphology of a variety of tropical regions in other parts of the world. On Java this aspect has as yet received little attention. However, in the hilly Tertiary terrains a set of subsequently rejuvenated planation surfaces can often be recognized. Efforts have now been made to localize raised beaches or abrasion surfaces in the Tertiary terrains in order to reconstruct regional uplifts in the area.

The tectonics and concomitant features in the Tertiary formations are of particular interest for deformation processes during the Quaternary period. Should deformation during the Quaternary be considered as a regional omnipresent phenomenon, or is it more concentrated around local centres? A next problem concerns the nature of deformation with respect to geological time. Is deformation a continuous process throughout the Quaternary, or is it confined to certain geological events? Thus should deformation be considered as a local reaction to previous geological events. More or less continuously active deformation processes might have had important repercussions on the geometrical shape of the Quaternary basins and their sediment fill.

During early phases of the study kabupatens in the coastal lowlands were systematically surveyed to collect data on most of the existing wells. In particular the abundant tube wells, be they self-flowing or equipped with a hand pump, appeared to be useful for the regional well inventory. Statistical methods are applied to the populations of tube wells for each kabupaten to unravel the (sub)-regional hydrostratigraphy. Correlations have also been performed between the statistically derived hydrostratigraphy within the coastal lowlands and the Quaternary geology in the hinterland, against the background of important events in this period. The hydrostratigraphy derived in this way has been further used as input for the vertical modelling of groundwater flow lines.

Groundwater hydrochemistry has been used primarily for the classification of chemical types to test the results of streamflow paths modelled by a vertical finite-difference procedure model. Another objective concerns the mechanisms of enrichment in total dissolved solids and salinization and, conversely flushing processes in the multiple aquifer systems.

A point of long-standing debate in publications on the groundwater situation in the coastal lowlands pertains to the Quaternary geological structures underlying the shallow Java Sea and the ability of the groundwater bodies to be incorporated in gravity-driven flow systems. The question arises whether the entire pile of Quaternary sediments, or perhaps even the top of the Tertiary strata, is being subjected to a flux by groundwater flow or whether it is a Toth system of hierarchically-nested flow systems in which the deeper systems remain largely unaffected. The effects on the groundwater flow patterns of the morphology of the coastal lowlands and the tectonics along the southern boundary with the hinterlands are given much attention in this study.

2.4 *Outline and order of chapters*

The order of chapters in the present study and the subjects to be discussed in each chapter approximately follows the upper right to lower left diagonal of Table 2.2. That is, descending from an overall earth scientific framework of large geo-scale and geological time span to lower levels of smaller time duration and scale, thereby zooming in on the various subsystems at the same rank and level.

In Chapter III the overall geo-framework is presented in terms of a consuming plate boundary model. The geological developments of major sedimentary basins and their general stratigraphic build-up are traced throughout the Tertiary period. Neogene strata and their Tertiary structures in the study area are discussed, based mainly on field observations. Tertiary climatic conditions are inferred from paleo-pedological evidence.

The Pleistocene emergence of Java is discussed in Chapter IV. The major geological developments, such as regional magmatic arc building, which have finally led to the present-day shape of the island are discussed in this chapter. Much attention is paid to tectonic structures in the Tertiary strata along the southern periphery of the coastal lowlands. Pleistocene climatic fluctuations as inferred from field evidence are treated in conjunction with the morphological processes.

In Chapter V the physiographic scale is further reduced from a plate segment to the region of the northern coastal lowlands and the Pleistocene geologic events are translated into sedimentary basin filling. The statistical analyses of well depth and the expected hydrostratigraphy are described in this chapter.

A reduction in time scale is accomplished in Chapter VI, whereas the physiographic scale is left unchanged from the previous chapter. Outcropping sedimentary units are discussed to discern regularities in sedimentation patterns. The region of the coastal lowlands is further divided into coherent morphological belts and zones.

The actual groundwater systems occurring in the various sub-regions and localities are described in detail in Chapter VII. A number of cross sections are presented, showing the expected groundwater flow patterns together with the hydrochemical types of groundwaters at various levels in the flow systems.

Finally, Chapter VIII gives a synthesis of the groundwater systems and driving mechanism embedded in the larger geological framework.

III. THE TERTIARY EVOLUTION OF JAVA IN A FRAMEWORK OF REGIONAL PLATE TECTONICS

3.1 Present-day regional plate tectonics setting

3.1.1 Introduction

The islands of Java and Sumatra with their well developed magmatic arc systems together with the submarine tectonic features such as the Java Trench and ridge systems are generally considered as typical examples of modern plate subduction systems. The basaltic plate of the Indian Ocean is thrust northwards underneath Java and Sumatra at velocities of a few centimetres per year, accompanied by substantial seismic activity in the Indonesian region. The major tectonic elements of a subduction system, i.e. the trench, outer-arc ridge, outer-arc basin, magmatic arc and back-arc basins are well developed and have been clearly delineated in the last two decades by geophysical surveys conducted by the major oil companies. Although back-arc basins are present in the Java-Sumatra arc systems, they are still grouped as continental arcs (Uyeda and Kanamori, 1979) because these back-arc basins are underlain by a continental or newly accreted semi-continental crust. Hamilton (1979) in his monograph on the *Tectonics in the Indonesian Region* summarizes the available geophysical information and re-examines old geological survey reports from the pre-war periods for specific features indicative of subduction systems.

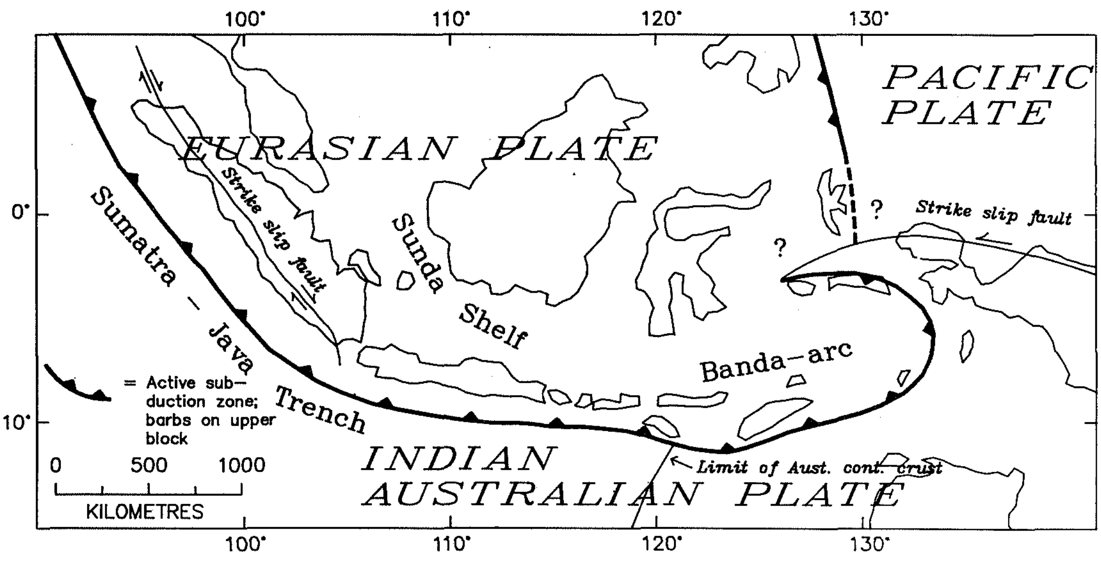


Fig. 3.1 Major lithospheric plates in the Indonesian Archipelago.

Three major lithospheric plates are found within the boundary of the Indonesian Archipelago, i.e. the Eurasian plate, the Indian-Australian plate and the Pacific plate with a triple junction in the vicinity of the island Ambon (see Fig. 3.1). The actual tectonic situation near the triple junction is much more complex than shown in Fig. 3.1, which stresses only the mosaic outline of the mega-plates.

3.1.2. *Main plate tectonic elements*

The principal tectonic elements of the Java subduction system are shown in Fig. 3.2 and the classical diagram of Fig. 3.3 depicts a general cross section perpendicular to the Java Trench system. The Java Trench marks the point where the oceanic plate underthrusts the seaward limbs of the outer arc ridge. Typical depths to the ocean floor in the trenches are in the order of 6,000 to 7,000 m off Java and become shallower in both the east and west directions.

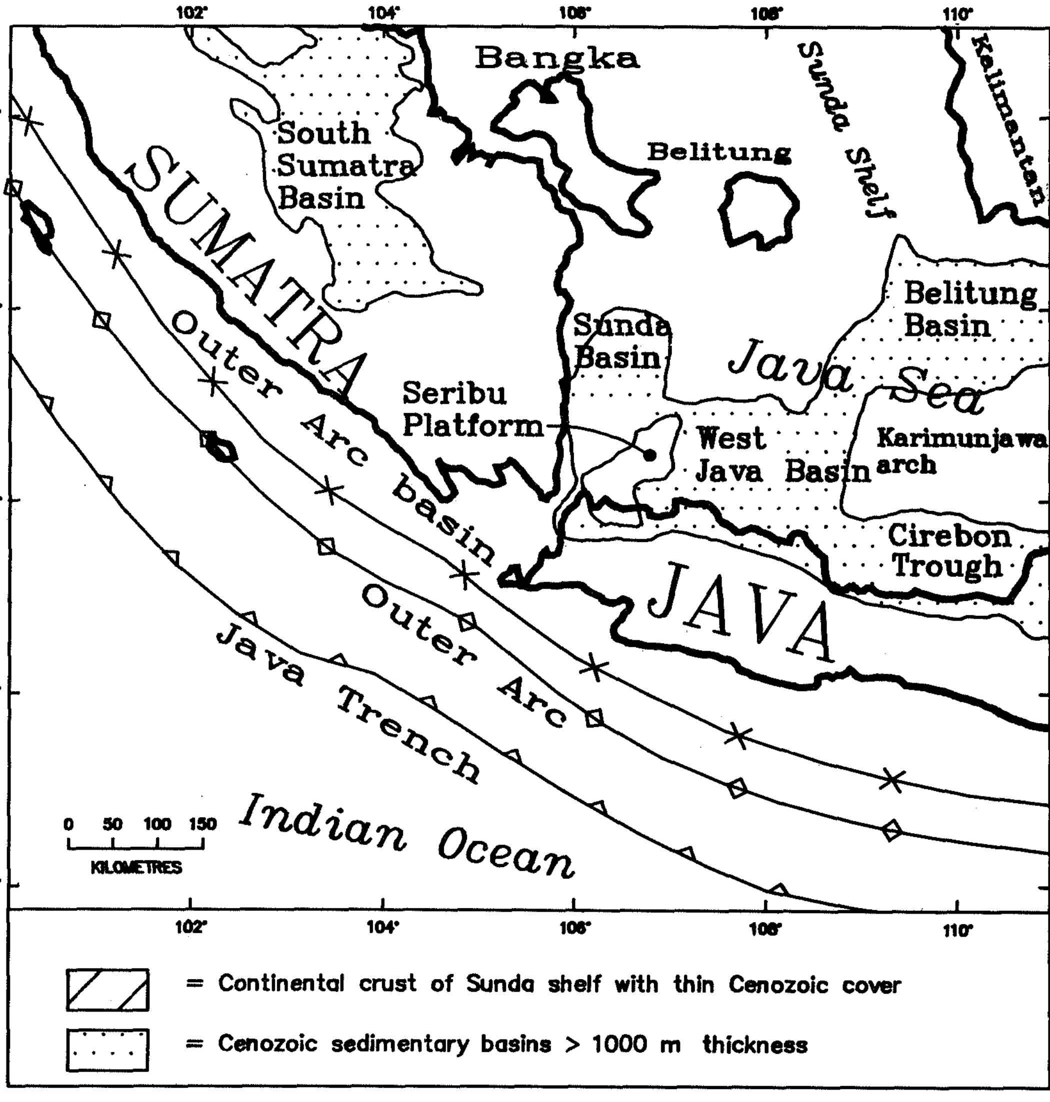


Fig. 3.2 Principal tectonic elements of the Java subduction system, partly after Batchelor (1979) and Hamilton (1979).

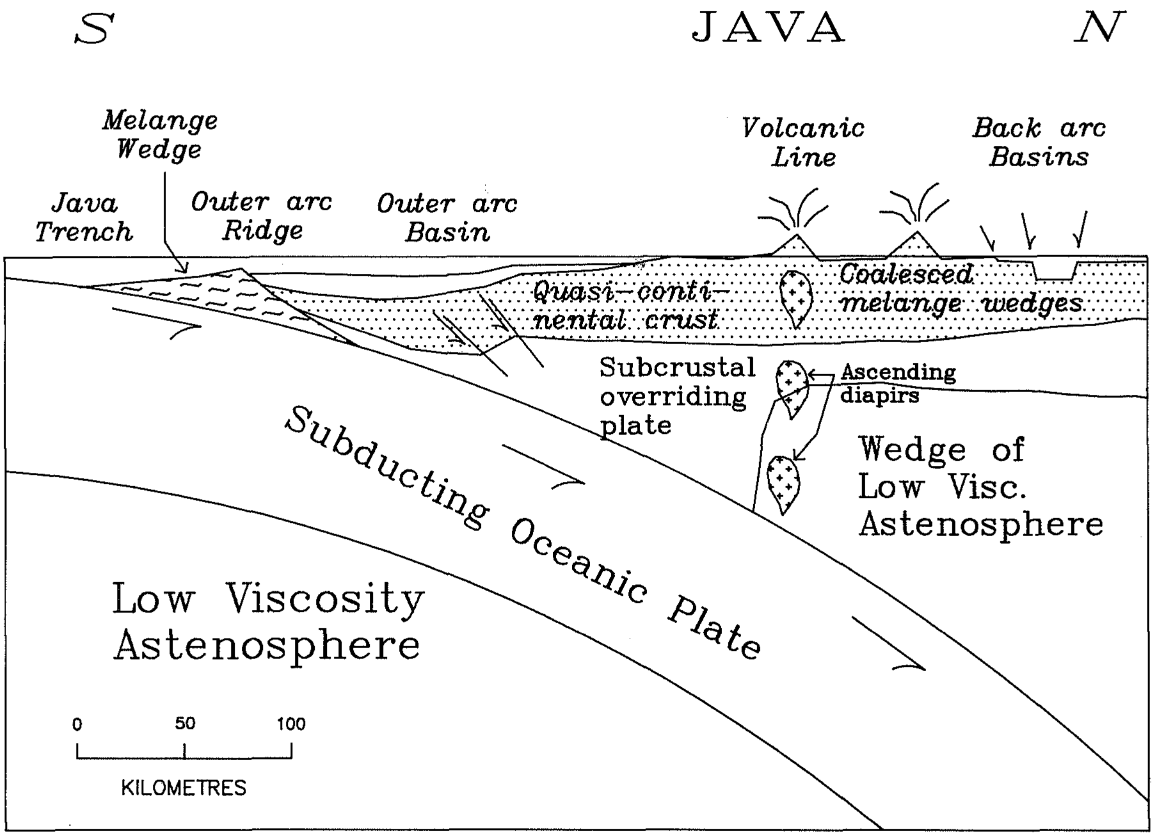


Fig. 3.3 Classical diagram of the Java subduction system.

Mainly thin pelagic sediments are found blanketing the ocean floor, with minor terrigenous sediments in the trench. The crest of the outer arc ridge is completely submerged along the Java subduction sector and lies at depths of 1,000 to 3,000 m below sea level. Islands are found west of Sumatra which mark the top of the ridge. The outer arc ridge is built up of an asymmetrical wedge of mostly moderately to highly deformed sediments and sedimentary rocks with imbricated fault structures and minor fragments of crystalline rocks (Hamilton, 1979).

This chaotic mixture of highly sheared and disrupted rocks is indicative for subduction melanges. Hamilton (1979) reports broken fragments of all sizes consisting of a wide variety of crystalline and sedimentary rocks, dispersed and mixed together in a ductile scaly clay matrix, as found on the island Nias west of Sumatra.

Fossil melanges of Late Cretaceous and Early Tertiary age are exposed in three small areas on Java. At a distance of 20 km east of Yogyakarta in the Jiwo hills (Central Java) an inlier is present exposing the underlying fossil melange. The larger parts of Java appear to be underlain by this fossil melange (see Fig. 3.4) which leads Hamilton (1979) to conclude that quasi-continental crust lies beneath Java built up by accretion of melange wedges. Details of this melange as surveyed by the present author, will be discussed in the next chapter.

The outer arc basin is a well developed structural basin bordering the shorelines of Sumatra and Java. Typical depths reach 3,000 to 4,000 m for the sector along the provinces West- and Central Java. A saddle in the outer arc basin is present in the Sunda strait between Java and Sumatra. Towards the East Java sector the basin becomes abruptly shallower. A thick pile of clastic sediments is deposited on the shelf by large rivers which drain catchments extending far into the magmatic belt of Java. The shelf off Java exhibits a width of 20 to 50 km and acts as a cascade system for the sediment transported towards the outer arc basin. Continuous loading of sediments on the shelf will trigger turbidity currents and huge sediment loads are then transferred to the system of the outer arc basin. The outer arc ridge apparently retains the sediments in the outer arc basin, preventing them from flowing into the trench. Hamilton (1979) is inclined to the opinion that important longitudinally flowing turbidity currents must take place, since the basin floor reveals a smooth shape. Hamilton even expects sediments from the shallower outer arc basin off Sumatra to flow by turbidity currents as far as the Java sector. The sediments in the outer arc basin are slightly deformed with thicknesses of up to 6 km. Towards the outer arc ridge the sediments become increasingly deformed, with overturned structures adjacent to the melange wedge.

3.1.3 Island-arc volcanism

Present-day volcanic activity is confined to a belt which runs parallel to the Java Trench. Outside this belt the volume of erupted magmas decreases markedly (Marsh, 1979). The actual mechanisms which lead to magma generation and subsequent volcanism are as yet not fully understood. However, volcanic arcs are related to subducting oceanic plates, with magma generation occurring at the upper part of the subducted oceanic slab. Consensus is evident in the literature, however (e.g. Le Pichon et al., 1976; Marsh, 1979; Kobayashi, 1983 and Kienle et al., 1983) on the average depth of about 120 km at which temperatures reach 750^{0}C, sufficient for partial melting of the top of oceanic basaltic slabs (see Fig. 3.3). Dehydration reactions in the upper part of the oceanic slab are likewise invoked to explain magma generation. The ascending of water and hot mantle materials is considered as an alternative mechanism. Positive correlations are established between the dip of the Benioff zone and the distance between the volcanic- and non-volcanic arcs and again between active volcano spacing and Benioff dip (Shimozura and Kubo, 1983; Kienle et al., 1983).

Van den Beukel & Wortel (1986) have applied a finite difference technique to model the temperature structure of a subduction zone. They conclude that mechanical friction only, due to underthrusting of the oceanic plate, does not lead to melting of the plate, but friction has a large influence on the temperatures in the arc-trench region. According to these authors the high temperatures of the astenospheric wedge above the oceanic slab cause the generation of magmas. The lack of a wedge in the case of small dipping subduction zones presumably explains the absence of a volcanic line. The thermal model results do not contradict the idea that the volcanic line corresponds to the astenospheric wedge boundary.

Island arc volcanism may vary strongly in time and space as stressed by Honza (1983), from periods of intense to almost no volcanism and periods of regional uplift, to widespread subsidences and basin formation. Important shifts of the volcanic arcs may occur within time spans of a few million years. With respect to Java, intense volcanism started in the Late Oligocene and Lower Miocene decreasing strongly, yet still noticeable in the sediment record, until the Upper Miocene when volcanism revived especially in the Lower Pliocene. A regional decrease in magmatic activity is again recorded in the Pliocene sediments, locally increasing towards the end of the epoch. The Pleistocene epoch displays a rather different pattern of volcanism, with explosive regional activities in approximately Middle Pleistocene times and a second period at the boundary Pleistocene-Holocene. The volcanic line appears to have shifted back and forth during this magmatic history. Situated at the southern boundary of present-day Java in Late Oligocene and Early Miocene times, the axis shifted north at the boundary between the Miocene and Pliocene. During the Pleistocene epoch the magmatic arc remained more or less at its present-day position.

These features of parallel shifting of volcanic lines and the apparent cyclic variations in magmatic activities on the scale of 'plate sectors/segments' and 'regions' are commonly found in volcanic island arcs and have also been described for areas such as Japan (Kobayashi, 1983; Honza, 1983) and the Aleutian Arc (Kienle et al., 1985).

3.2 *Tertiary evolution of the Java island arc*

3.2.1 *Paleogene fossil melanges*

The oldest rocks exposed on Java are found in three relatively small melange terrains dating presumably from Upper Cretaceous and Early Tertiary times. The three areas are indicated on Fig. 3.4; one is situated in the southwestern part of Java (Gunung Cikeruh near the Pelabuhanratu Bay) and the other areas are both to be found in Central Java (River Lukulo, Karangsambung, South Serayu mountains and Bayat, Klaten).

Van Bemmelen (1949) describes a complicated structure for the melange terrain in southwest Java, consisting of gabbros, peridotites and serpentinites with dynamic metamorphosed sedimentary rocks, partly thrust upon overlying Eocene beds. The small fossil melange terrain in the eastern part of Central Java, in the Jiwo hills near Bayat and 35 km east of Yogyakarta, was examined by the present author.

The surmised tectonic melange is exposed in two isolated hills in a broad E-W trending valley covered by alluvial deposits. The hills consist mainly of green schists with minor occurrences of slates and phyllites. A deeply weathered diorite/gabbro is exposed in the southern flanks of both hills. These batholiths appear to have intruded later into the melange complex, presumably in Lower Miocene times, and are related to the Miocene volcanic and intrusive diorite complexes both on the western side (Kulon Progo) and eastern sides of the Jiwo hills. Abundant aplite dykes and quartz veins extend into the melange complex. Many good quality exposures show the typical features of the melanges, that is to say strongly sheared and contorted schists and phyllites with 'floating' fragments and chunks of all sizes of more resistant sedimentary rocks. The foliation of the metamorphic rocks may change abruptly from a regular orientation to a disordered mess in which original structures are completely obliterated. Numerous minor faults are present on the scale of an exposure, bounding slices of greenschists. Slices of serpentinite and zones with hydrothermal alterations to talc have been found in exposures in the western hill. Remarkable are the fragments of light to dark grey pelagic cherts with cm-sized fragments of light coloured sandstone as flattened, lenticular-shaped and rotated cataclasts. In one exposure red abyssal clays have been found as local thin layers in the contorted schists. Fragments of lithic sandstones, clay stones, and disrupted and boudinaged quartz veins are present in the greenschists. These quartz veins are not related to the Lower Miocene diorite intrusive complexes, but are much older and limited to the melange rocks only. Hamilton (1979) explains the presence of these anomalous sheared quartz veins as melting on contact of the melange wedge with the hot subducted oceanic plate.

Eocene limestones with Nummulites are present, which have apparently been developed as fringing reefs around islands of melange wedges. The intruded diorite/gabbro clearly dislocated a large lens of limestone and caused thermal metamorphism.

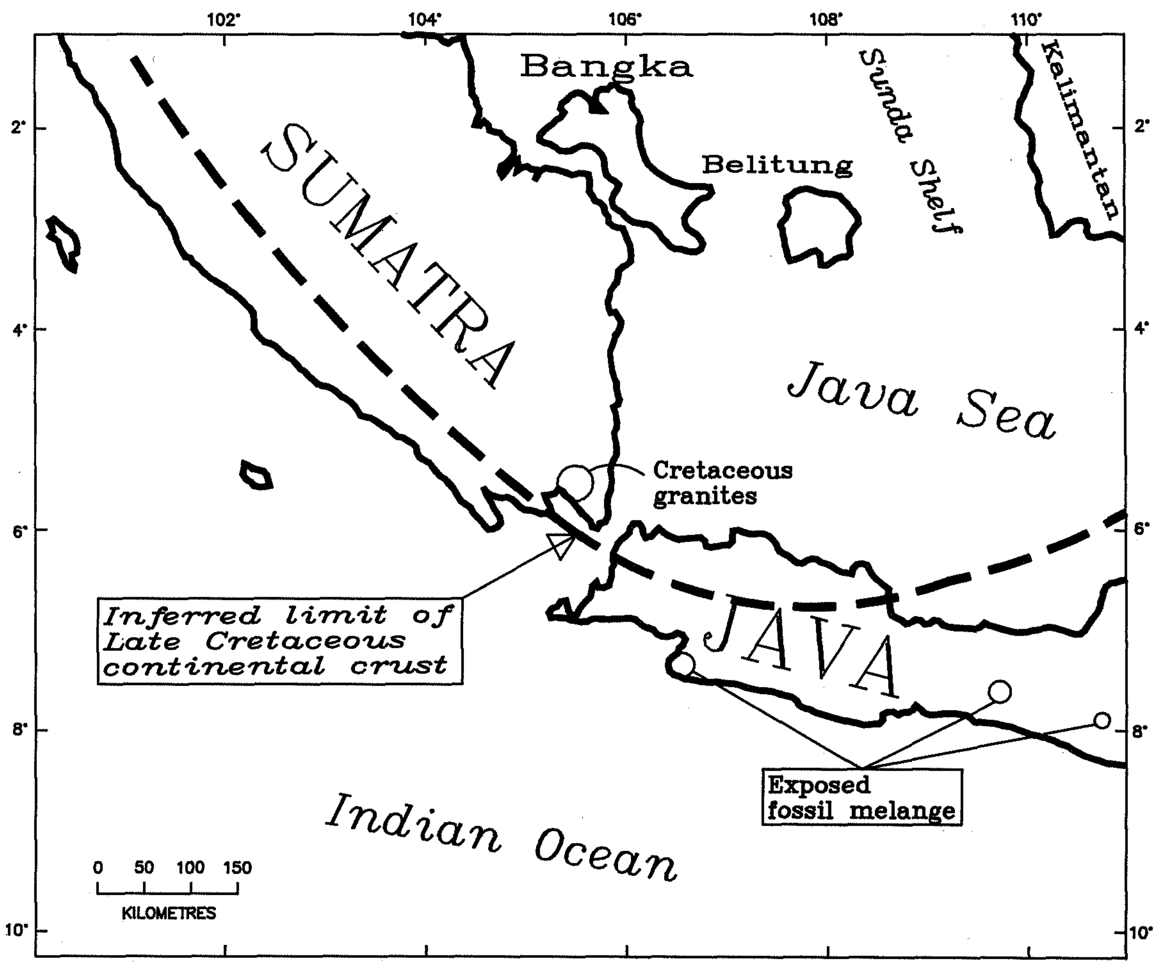


Fig. 3.4 Melange terrains and inferred limit of continental crust during Late Cretaceous and Early Tertiary, modified after Hamilton (1979).

In an exposure in the eastern hill, limestone fragments sizing from a few cm to blocks of 10 to 20 m and completely marmorized, are 'floating' in a matrix of highly sheared greenschists and phyllites. In places the ductile metamorphic rocks are squeezed out between the larger blocks. These limestone blocks without recognizable fossils are completely different from the Eocene Nummulitic limestones. From the local occurrence and the position in the highly sheared phyllites, these limestone blocks and lenses are jumbled into the melange and may represent Cretaceous carbonates, presumably pelagic limestones.

The position of these Upper Cretaceous and Early Tertiary melanges yield some clues to the position of the subduction system at that time. The fossil melange marks the approximate position of the subduction system at the beginning of the Tertiary period. With the configuration of the exposed Upper Paleozoic and Mesozoic continental crust terrains in Kalimantan (Borneo), Bangka, Belitung and a Cretaceous granite in southeast Sumatra, along the Sunda Strait, the boundary of the Cretaceous crust runs from Sumatra to the western part of Java on the northern side of the fossil melange terrains, crossing the Java Sea (Sunda shelf) and trending to the eastern part of Kalimantan (see Fig. 3.4).

Assuming active subduction at the beginning of the Paleogene, a volcanic arc must have formed slightly north of the northern coast of present-day Java. Hamilton (1979) reports on the abundance of Upper Cretaceous to Lower Paleogene volcanic rocks in the basement of the Java Sea.

3.2.2 *Major plate events in the Indian Ocean*

As was elucidated in an earlier chapter concerning the methodology of this present study, the plate tectonics in the Indonesian Archipelago may be better understood by first studying the entire framework of lithospheric plates in the Indian Ocean. It stands to reason that the evolution of plate tectonics in the Indonesian Archipelago during the Tertiary period, should be seen in a much wider context of mega-plate events in the Indian Ocean. In fact the history of the breakup of the Pangea continent may yield important clues to the understanding of Java geology. This approach concurs with the methodology set out in the foregoing chapter.

General agreement is evident among earth scientists that about 200 million years ago the present-day continents fitted together in one universal land mass Pangea. At that time the breakup of this primeval continent started with a rift which began to isolate the northern group North America and Eurasia from the southern group consisting of Africa, South America, Antarctica, India and Australia. At the end of the Triassic period, about 180 million years ago, the rifting of Pangea proceeded in the Central North Atlantic, between Africa and North America and between Africa-South America, and Madagascar-India-Australia-Antarctica (Dietz and Holden, 1970; Le Pichon et al., 1985). The rifting, accompanied by sinistral rotation of Africa-South America, resulted in a gradual closure of the Tethys and a zone of crustal uptake from Gibraltar to the area of Kalimantan. The continental crusts of both Sumatra and Kalimantan once formed the protruding southeast edge of the Eurasian continent. The Mesozoic granitic rocks as found on the island of Bangka and Belitung, southeast of Sumatra, may be related to this Mesozoic subduction zone. Fossil magmatic belts and melange terrains of Mesozoic age are also present in the southern and eastern part of Kalimantan trending in a curve towards Sumatra, expressing the protruding shape of this part of the Eurasian continent which was apparently fringed by subduction zones at that time.

Sharma (1987) assumes active spreading centres in the Tethys about 160 Ma ago based on the development of a volcanic island arc close to the southern margin of Asia. Hilde et al. (1977) in an attempt to reconstruct plate boundaries in the Tethys sea at 190 Ma ago assume a long subduction zone fringing the Eurasian continent. The arc activities continued through the Cretaceous up to the Paleocene. Hamilton (1979) mentions extremely sheared slaty meta-sediments in the Sunda shelf basement north of East Java with Potassium-Argon ages of about 100 million years and further widespread silicic igneous rocks north of West Java with K-Ar ages ranging from 58 to 140 million years. Based on the abundance of age determinations, Hamilton suggests that the silicic magmatism is related to the same subduction system as of the Late Cretaceous and Early Tertiary melanges found on Java.

Le Pichon et al. (1985) mentions a second major event in the Indian Ocean, the rifting away of India 80 Ma ago. This rift between Australia-Antarctica and India took place in Upper Cretaceous times, ushering the period of a spectacular 5,000 km northward drift of the Indian continent from its position interlocked between South Africa and Antarctica to its present position. As a third major plate event in the Indian Ocean region the separation of Australia from Antarctica, 54 Ma ago can be mentioned (Le Pichon et al. 1985; Hilde et al., 1977).

Table 3.1 Summary of major plate events in the Indian Ocean (after Le Pichon et al., 1985).

180 Ma	Rifting between North America and Africa and between Africa-South America and Madagascar-India-Australia-Antarctica. Pangea still remains within the original great circle. Closure of the Tethys.
80 Ma	Rifting between Australia-Antarctica and India. India is set free to start travelling to the north at a speed of 16 cm/year along the geoid slope. Australia-Antarctica rotates clockwise out of the Pangea circle towards the negative geoid belt. Widening of the Tethys. Migration of Eurasia out of the Pangea great circle in an eastward direction.
70 Ma	Rifting between Australasia and Antarctica.
54 Ma	Complete reorganization of oceanic spreading centres took place in the Indian Ocean with a jump of the ridge between Eurasia and Australia to between Australia and Antarctica. Australia appears to become coupled to the Indian oceanic plate.
42 Ma	Drastic change in direction of the Pacific plate from NWN to WNW with respect to Eurasia (Morgan, 1972).
35 Ma	Eurasia is now almost stabilized over the negative geoid belt after a drift over the Pacific of about 3,000 km at the Japan latitude. First stage of India collision. Spreading in the area of the present-day Java Sea and formation of the Neogene basins. Widespread Oligocene regression (Vail et al., 1977).
20 Ma	Eurasia movements have terminated. South New Guinea collides with the volcanic arc which will form North New Guinea. India collides completely with Eurasia. Rotation of Indo-Chinese Peninsula by an opening of the South Chinese Sea.
5 Ma	Collision of the continent of Australia with the Banda arc (Cloetingh, 1986).

During this event, a major reorganization of accretion boundaries took place during which the rift between India and Australasia died out completely. The collision of the continent of India with Eurasia about 35 Ma ago may have had consequences even for the Indonesian Archipelago, since expulsion of the Indo-Chinese peninsula from Eurasia is postulated by Le Pichon et al. to have been triggered by the India collision.

The creation of the back-arc basins such as the Neogene basins (see Fig. 3.2) found beneath the present-day Java Sea are thought to have occurred during the time span 32 to 17 Ma ago.

Plate tectonic events in the Indian Ocean are not merely confined to oceanic lithospheric plates but should also include drifting motions of the continents. Le Pichon et al. (1985) stress the independent motions of continents in relation to the geoid configuration and argue that the significance of these motions are greatly underestimated. Recent literature on plate tectonic events in the Indian and Pacific Ocean frequently mention the events at 80 and 54 Ma ago. The hypothesis is advanced by Le Pichon et al. that continental drift activity has peaked from 80 to 54 Ma ago. These workers are convinced of the importance of the geoid, which is closely related to the axis of earth rotation and that the low-order harmonics in the geoid are caused by lower mantle convection, which is in turn thought to be weakly coupled to the upper mantle convection. The effect of lower mantle convection is found in the tennis-ball shaped geoid. In their view the periphery of the Pangea continent coincided with a great circle through the paleo-poles. The centre of gravity of Pangea was then situated on the paleo-equator, thus within the positive geoid belt.

After the break-up of Pangea the continental motions were governed by deeper mantle convection and the continents appear to have moved down the geoid slope to belts of the negative geoid. Once the centres of gravity of the continents had reached the negative belts in the geoid, motions slowed down considerably and the continents became stabilized. Summarizing the major events in the Indian Ocean, based on the work of Le Pichon et al. (1985), one arrives at the sequence enumerated in Table 3.1.

Returning to the geology and stratigraphy of Java, the plate movements and events in the Indian Ocean during the Tertiary are considered to be of paramount importance. It stands to reason, as argued above, that separations of continents and reorganizations of plates and rifting zones in the very complicated Indian Ocean will have profound effects on the trenches and subduction rates at the convergent plate margins south of continental Asia. A correlation will be made between the Indian Ocean plate events and the geological development of Java during the Tertiary. It is shown that to understand the geology of Java requires consideration of the entire plate framework of the Indian Ocean.

Hamilton (1979) notes that after formation of the Late Cretaceous and Early Tertiary melanges, as described above, a relatively stable and tectonically quiet continental shelf extended to the edge of the open Indian Ocean during much of the Paleogene. Chiefly shelf carbonates and clastic sediments are recorded for the Middle Eocene through Middle Oligocene, apparently without volcanic rocks from eruption centres within Java. An offshore oil exploration well, south of Yogyakarta, the Shell Alveolina well, penetrates Tertiary volcanic rocks as old as Late Oligocene. Based on field observations all over Java by the present author, abundant volcanogenic rocks are commonly found in the stratigraphic record near the time boundaries Late Oligocene-Early Miocene, Late Miocene-Early Pliocene and the Quaternary period. As inferred from deep-ocean floor sediments (Hamilton, 1979), chrons of peak magmatism in the Indonesian region appear to have occurred in the Late Miocene and the Late Pliocene-Quaternary. In chapters on the Neogene rocks south of the northern coastal lowlands the geology will be elaborated further.

The relatively quiet time span from Middle Eocene to Middle Oligocene, lacking major volcanism and tectonics, is conspicuous. Many outcrops of Eocene rocks were examined by the present author in Central Java, revealing such silicaclastic rocks as marine micaceous siltstones, silica shales, quartz beach sands with lignites, quartz conglomerates and reef limestones, apparently without volcanics. Hamilton constructs the rationale that Eocene and Oligocene oceanic plate subduction could have been situated at another location. He suggests northwestern Kalimantan as the location in order to account for major crustal convergence, but immediately adds that the relative motions of other plate components in this surmised subduction setting remain uncertain. In the present study a different view is presented. Hamilton presupposes the oceanic plate movements to be more or less constant, or at least moving continuously. Le Pichon et al. (1985) notice the absence of any significant change in total accretion rate within the Atlantic and Indian Oceans. It is a matter of which geometric reference points are considered in the plate movements. Total accretion rates of oceanic crust may remain more or less the same, but the net subduction rates along the active continental margins may vary significantly by counteracting motions of the continents.

Viewed against the background of well known major plate events in the Indian Ocean, the outset of the tectonically quiet time span from Middle Eocene to Middle-Late Oligocene matches excellently the reorganization of spreading centres in the Indian Ocean. The jump of the ridge from Eurasia and Australia to between Australia and Antarctica, during which Australia became coupled to the Indian Oceanic plate, must have exerted an influence on subduction processes along the Java Trench. This reorganization of spreading centres is thought to be responsible for the drastic decline in subduction rates along the Java Trench. It is interesting to note that different patterns of volcanic arc-subduction zones existed prior to Eocene-Oligocene times compared to Neogene magmatic arcs. The former being arrayed concentrically around the old continental nucleus of Sumatra and Kalimantan and the latter constituting a long straight arc in eastward direction.

The effect of motions of the Eurasian continent at that time may have been limited as the drift of Eurasia was mainly directed eastwards, thus approximately parallelling the strike of the trench. Correlations between the geological record of Java and the motions of Eurasia, as estimated by Le Pichon et al. (1985), are difficult to establish conclusively but could exist. Significant subduction rates along the Java Trench may have already been restored in the Lower Oligocene (35 Ma), but regional magmatism appeared only at the chronological boundary Oligocene-Miocene due to the initial lack of a Benioff zone beneath Java.

The 35 Ma plate event, coinciding with a completion of a major change of the Pacific Oceanic plate motion and the stabilization of Eurasia, is also of regional importance for the Indonesian area. Stretching in the area of the Java Sea led to warping and block faulting, thereby creating zones of crustal weakness for the Neogene sedimentary basins in this area. The first collision contact of India with Eurasia deformed the subduction zone on the southern edge of Eurasia.

At 20 Ma (Early Miocene), thus during the first regional magmatism on Java, the collision of India with Eurasia was complete. It may have triggered expulsion of the Indo-Chinese Peninsula from the Eurasian continent. Notwithstanding the importance of these regional plate tectonic developments, including also the collision of South New Guinea, it is unlikely that the Late Oligocene-Early Miocene volcanism on Java can be explained by these continental collisions only. The historical evolution of volcanism in the Java arc is too universal and shows many similarities with other volcanic arcs such as found in the Japanese region (Honza, 1983).

In Late Miocene-Early Pliocene (5 Ma ago) an important collision took place in the Indonesian Archipelago; the collision of the Australian continent with the Banda arc. Drastic stress changes are surmised due to initial tensional stresses in the old oceanic subducted plate being converted to intensive compressional stresses by the approach of the buoyant continental lithosphere of Australia at the trench.

Considering the historical evolution of volcanic arcs, not only in the Indonesian region but also in typical arc areas such as Japan and the Aleutian arc, similar cyclic patterns appear to exist in arc volcanism, periods of uplift, subsidence and spreading, though albeit at different time and distance scales. The ultimate driving force, however, for arc volcanism and related tectonics is oceanic lithospheric plate subduction. Consequently, a drastic change in mega-plate motion directions or accreting oceanic boundaries must have their effects on arc volcanism. Generally two types of cycles in arc volcanism can be distinguished, viz.: a long and irregular cycle of tens of millions of years and shorter more regular cycles with durations of a few million years. These will be described in more detail in section 3.2.3. The long irregular cycles with epoch time scales, affecting active subduction margins along mega-plates, are thought to be induced by drastic mega-plate motion changes and accreting boundary reorganizations. The effect along the active margins is a drop in subduction rates, changes in dip of the subducted slab, oceanward shifting of trench (Wortel, 1986), stretching and subsidence in overriding plate, loss of the downgoing slab, cessation of volcanism and the beginning of a period of tectonic quiescence. Once the oceanic spreading zones are revived, subduction reestablishes itself first by ridge push, implying that it takes a certain time before the downgoing slab reaches a depth of about 100 km for magma generation to start, then magma should ascend through the crust before volcanism eventually reappears. Afterwards, local cycles of arc volcanism, uplifts etc. will regain importance and dominate at scales of regions and plate segments and at time scales of epochs (see section 3.2.3). The local cycles appear to be controlled by parallel systems all driven by the plate subduction. These pulsate in their own cycles as a result of differences in oceanic slab dip, subduction rates and plate stress conditions. In relation to stress conditions, Ida (1983) states that for the Japan region compressional and extensional stress fields appeared alternately every few million years and that such stress transitions were usually accompanied by violent volcanic activity. Viewed against this model, it follows that the revival of regional volcanism during the Late Oligocene-Early Miocene must then be explained as being related to mega-plate reorganizations in the Indian Ocean 54 Ma ago and the subsequent reestablishing of subduction. The smaller cycles of peak magmatism in Late Miocene-Early Pliocene and further during the Quaternary may then be explained as local systems on the scale of plate segments (Java segments and subsegments). Thus the second peak in magmatic activity on Java at the Miocene-Lower Pliocene boundary (about 5 Ma ago) can be correlated with the rapid reversals in stress fields resulting from collision of the Australian continent with the Banda Arc (see Fig. 3.1).

An important aspect in the stratigraphic record of Java and the Neogene basins underneath the present-day Java Sea is the apparent fluctuation of sea levels in relation to plate tectonics. Generally two types can be distinguished viz., those with a global character and those with rapid short-term fluctuations which are confined to depositional environments on a regional or plate segment scale. Vail et al. (1977) published their famous curves for sea level fluctuations based on data from passive margins and intracratonic basins from all over the world. The plate tectonic mechanisms which may cause these global fluctuations are still intensively debated. Since the Late Cretaceous the general tendency is a falling global sea level. Total accretion rates at oceanic spreading centres are generally invoked as the main cause, and are believed to have peaked at 110 Ma ago (Kominz, 1984). Increasing total ocean areas, as a result of continental collision, are likewise advanced by Le Pichon et al., (1985) who assume a total global sea level drop of 200 m since 80 Ma ago. However, no consensus exists among the various workers concerning these estimates, which vary from 50 to 350 m of sea level fall since Late Cretaceous up to Late Cainozoic eustatic rises from -1000 m to present levels (Batchelor, 1979). Cloetingh (1986) argues that changes in the stress fields of lithospheric plates may result in apparent sea level changes of several tens of metres along flanks of sedimentary basins in passive margin settings. With this hypothesis Cloetingh attempts to explain the rapid short-term fluctuations along passive margins of one plate or one plate segment and thus regional fluctuations. It is further stated that similar fluctuations can be induced along active continental margins or in general along convergent plate boundaries simply by changes in the plate stress fields, which may in turn also influence intracratonic basins near the plate margins. For fluctuations with amplitudes of more than 50 m changes in stress fields are required, attainable only by global plate reorganizations. A widely recognized event in global sea level changes is the 'Middle Oligocene regression' which appears to coincide with the 35 Ma plate event. Although this conspicuous Middle Oligocene sea level fall might be attributed to glacial fluctuations, Cloetingh & Wortel (1985) argue that the interaction between deflection of the lithosphere, due to sediment loading, and changes of sufficient magnitude in horizontal intraplate stress fields in oceanic lithospheric plates, may account equally well for apparent sea level changes in the order of 100 m within a few million years at the sedimentary basin flanks. This therefore provides an alternative mechanism for the so-called glacial sea level fluctuations. Nevertheless, due to its global nature the mid-Oligocene sea level lowering is generally attributed by most workers to global plate reorganizations at 35 Ma ago, presumably with an additional glacial effect of eustatic sea level fall.

The lithospheric plates, if considered as thin elastic sheets floating over a fluid substratum, will deflect under supercrustal loads. The flexural rigidity of the plate or equivalent elastic thickness is one of the mechanical parameters which determines the total vertical displacement of the deflection. Resulting from cooling and thickening of the oceanic lithosphere, the flexural rigidity appears to increase with the age of the oceanic lithosphere. Horizontal intraplate stresses also have an impact on the flexural rigidity.

> Intraplate compressional stresses appear to buckle a sedimentary basin, implying a relative subsidence along the axis and a relative uplift of the basin flanks. Conversely, tensional stresses tend to stretch the deflection under the sediment load, producing a relative uplift along the axis and relative subsidence at the flanks. Relative uplifts or subsidences are in fact a function of sediment loading, intraplate stress fields and the age of the lithosphere (Cloetingh, 1986). Apparent sea level changes caused by changing intraplate stresses are most effective in the case of thick sediment wedges resting on young oceanic lithospheric plates, thus in particular in passive margin settings. Collisions along other sectors of the plate margin, such as the India, South New Guinea and Banda arc collision may also have influenced plate stresses along the Java Trench.

The driving forces of the subducted oceanic plates are the ridge push at the centres of sea-floor spreading and the pull forces on the downgoing slab. The slab pull is thought to be balanced by resistive shearing forces acting on the downgoing slab (Wortel, 1986). The slab pull forces become the dominant driving force for the older subducted oceanic crusts such as found underneath Java. Uncompensation or overcompensation of the slab pull forces may vary considerably along convergent plate boundaries as pointed out by Wortel (1986). Hilde (1983) describes the intra-plate stresses along the Java- and Sumatra Trenches and concludes that the Sumatra Trench is characterized by compressional forces, whereas tensional stresses dominate the older oceanic crust along the Java Trench. Thus even along a single trench system stress fields may vary widely. Conceivably, variations in activities at the ridge systems must have impacts on the ridge push forces. The ridge push is not a single force acting at the ridge axis, but a pressure gradient, according to Lister (1975), caused presumably by cooling and increasing density of the hot oceanic lithospheric plate. Transitions from tensional intraplate stresses to compressional stress during increased activation of sea-floor spreading may lead to apparent falls in sea level at the edge of basins along active and passive continental margins. Vice versa, transition from compression to tensional stresses during slowed down plate movements or dying out ridge systems will induce apparent sea level rises.

Van Bemmelen (1949) mentions a general transgressional trend during the Eocene to Middle Oligocene. In the Paleogene terrains exposed in the southwestern part of the province of West Java, cross-bedded quartz sandstones, conglomerates and lignite seams are overlain by marls and reef limestones. Volcanic rocks are apparently lacking, as can be judged from the scanty terrains, exposing Paleogene rocks. Van Bemmelen (1949) on the other hand, describes his 'Old andesite' volcanism as being included in the Paleogene rocks of the Bajah mountains in West Java and in the Kulon Progo mountains in south Middle Java. Thus Paleogene volcanism forms a row of volcanic islands, contrary to the quiet Eocene and Oligocene scenery described above. However, field surveys conducted by the Geological Survey of Indonesia evidently indicated a Lower Miocene age for the 'Old Andesites' in the Bajah and Kulon Progo mountains. Hamilton (1979) is convinced of the erroneous age assignments of Van Bemmelen's 'Old Andesites' and likewise prefers a Miocene age. The transition Oligo-Miocene is characterized by an important break in the stratigraphic record, a disconformity as reported by Van Bemmelen (1949). This author advances the possibility that the scarcity of Oligocene deposits is related to regional erosion after the Middle Oligocene, which corresponds well with the widely recognized Middle Oligocene regression.

At present a slab pull force prevails in the fairly old (140 Ma) oceanic lithosphere subducted along the Java Trench sector. With these tensional stresses in the oceanic slab, graben structures may develop at the trench (Wortel, 1986) in which sediments become trapped and may be carried downwards along the Benioff zone. Hence, the process of scraping sediments from the subducted slab may now have largely ceased. The Late Cretaceous to Paleogene melange exposed in three terrains on Java probably indicates the opposite situation of compressional stresses at that time, thus forming the melange wedge by scraping and accreting them onto the continent.

Present-day stress fields for the Indonesian region shows a compressional field in the lithospheric plate thrust under Sumatra and a tensional field in the slab subducted under Java. The present compressional stresses off Sumatra are aligned more or less parallel to the longitudinal axis (Geller et al., 1983). The dextral Barisan strike-slip fault, running SE-NW along Sumatra, might be related to the stress pattern in the oceanic lithosphere west of

Sumatra. In the area of the Banda arc, east of Flores, compressional stresses are dominating due to the collision of the Australian continent.

In summarizing the general stratigraphic record of Java in relation to the major plate tectonic events, it can be said that geological developments during the Tertiary fit remarkably well with major plate tectonic events in the Indian Ocean. The Cretaceous and Paleocene melange terrains were developed during a time span from 135 to 54 Ma ago when a young Indian Oceanic slab was subducted, mainly driven by the ridge push. The oceanic spreading centres at that time were situated at a distance of perhaps not more than 3,000 kilometres from the subduction complex. The tectonically quiet time span on Java from Lower Eocene to Middle Oligocene are supposedly caused by drastic changes in subduction rates as a result of the complete reorganization of oceanic spreading ridges at 54 Ma ago in the Indian Ocean. This event may have led to such drastic changes that subduction even may has ceased, so that the downgoing slab beneath Java was lost and sank into the astenosphere. Once subduction was reestablished or reinvigorated, presumably around 35 Ma ago, it took a few million years before magmatism reappeared. Drastic declines in subduction rates along the Sumatra-Java Trench are thus linked to mega-plate tectonics at spreading centres in the Indian Ocean. The Late Miocene-Lower Pliocene and presumably Quaternary volcanism on Java can be explained as plate tectonics at the scale of plate segments and sectors along the subduction complex, thus entirely at the other end of the spreading-subduction systems. The event at 5 Ma ago (Late Miocene-Lower Pliocene), consisting of the first collision contact of the continental lithosphere of Australia with the Banda arc, must have given rise to radical plate stress reversals and correlates well with the magmatic peak at that time on Java.

The relation between motions of the Eurasian continent towards the negative belts in the geoid, from about 80 to 54 Ma ago, and the geological developments on Java are hard to establish.

3.2.3 Synopsis of geological developments in West- and Central Java during the Tertiary

The available geological information on Java in the form of maps issued by the Geological Survey of Indonesia, at Bandung, and the papers and articles published during the last two decades in the framework of extensive oil exploration, make it possible to reconstruct in broad outline geological developments during the Tertiary. Based on the 1:100,000 scale geological map sheets covering the major parts of West- and Central Java, an attempt is made to extract per epoch the most characteristic lithologies. A correlation is made with the major plate tectonic events in the Indian Ocean as elaborated previously. Table 3.2 lists the stratigraphic record for West- and Central Java and major plate events.

Late Cretaceous and Paleocene rocks are found only in exposed fossil melanges on Java. Oceanic plate consumption took place along the entire Java Trench at the beginning of the Tertiary and sediments and slices of oceanic crust were scraped off by the overriding quasi-continental plate margin and accreted as a tectonic melange onto the outer-arc ridge. It can be inferred from the melange wedges and abundant igneous rocks of similar age in the crustal basement beneath the Java Sea (exposed with Lower Tertiary quartzose erosion products on the Karimunjawa islands forming part of the Karimunjawa arch; see Fig. 3.2), that all the tectonic elements of an active subduction system were well developed.

Compared to the formation of melanges near the Java Trench, the following factors can be mentioned which distinguish Late Cretaceous to Early Tertiary melanges from present ones:

1) the young and hot oceanic plate with the oceanic spreading centre close to Java;
2) presumably small dips of the oceanic plate with relatively low specific density, causing difficulties in underthrusting;
3) ridge push was the main driving factor in underthrusting, whereas nowadays ridge pull dominates in the old oceanic plate;
4) thin but long melange wedge cross section, active melange wedge building by accreting sediments;
5) the boundary between the melange wedge buttressed against the toes of the quasi-continental crust under Java may have been rather diffused and slices of the crust may have been mixed into the melange;
6) as a result of the diffuse boundary mentioned in 5, large parts of the outer-arc basin sediments may also have been involved in the imbrication and rotation movements in the wedges;
7) the young and hot oceanic lithosphere may have played an important role in metamorphism of the melange wedges.

In this volcanic arc framework it appears that the pre-Tertiary basement of the Java Sea was not faulted into basins and presumably formed a continental landmass pierced by magmas, intruded by batholiths and partly overlain by volcanic rocks. The 54 Ma plate event resulted in drastic declines in subduction or even cessation, causing gravitational collapse, spreading of the melange wedges and vanishing volcanic activity. The subducted oceanic slab may have broken off and sunk into the asthenosphere, thereby heating up and losing its identity.

A period of tectonic quiescence is recorded by lithologies of the Middle Eocene to Middle Oligocene series. The quartzose cross-bedded sandstones, conglomerates and the marine siliceous shales, mudstones, siltstones and beach sands intercalated by lignites, apparently without volcanic materials, indicate relatively stable continental environments of alluvial plains and coastal lowlands. The provenance of quartzose clastic materials was to be found in the continental land mass to the north, which was fringed by broad alluvial plains and coastal lowlands. The collapsing melange wedges and outer-arc ridges may have existed as island arcs, which finally became base-leveled and overlain by fringing reef limestones during the Eocene. The Eocene sediments which lie unconformably on the basement of the Java Sea are terrestrial silicaclastic rocks, indicating, together with the abundant cross-bedded sandstones and quartz conglomerates in Central Java, widespread continental settings.

The Oligocene sediments, although rarely exposed, are developed as reef limestones, marls, marly clays interfingering with quartz sandstones, indicating a regional transgression. Most of the sediments may have been removed by erosion after the Middle Oligocene regression. The decrease or even cessation of subduction, as can be inferred from the sedimentary environment, is translated into a change from intraplate compressional to tensional stresses as a result of the continuing pull from the broken off and sinking underthrust oceanic slab. A change from compression to tensional intraplate stresses is accompanied by an apparent rise in sea level at the flanks of active and passive margin basins, which seems to correspond with the transgressional trends from Middle Eocene to Middle Oligocene. Another mechanism, suggested by Wortel (1986) to explain the transgressional trend is the increasing magnitude of slab pull which forces the trench to shift oceanward and induces stretching and subsidence in the overriding plate. The reactivation of subduction about 35 Ma ago is expressed in the Oligo-Miocene unconformity, with removal of major parts of Oligocene and Eocene strata and the generation of voluminous volcanic rocks erupted from Late Oligocene to Lower Miocene.

Table 3.2 Characteristic Java lithologies and major plate events in the Indian Ocean.

	TIME in mill. years	EPOCH	AGE	GENERAL LITHOLOGY	DEPOSITIONAL ENVIRONMENTS	PLATE EVENTS and TECTONICS	VOLCANISM
Q T	1.6	Pleistocene		Volcanics, vast mud shelfs	Terrestr.,deep, shallow marine	Active subduc. old ocean crust	Widespread volcano rows
T	6	Pliocene	U ----- L	Marls; lignites sandstones Clays; marls Crystal tuffs; volc. breccias	Littoral; coastal lowlands in N. Java; shallow marine Continental	Increased subduction ?	Reactivated magmatism
E R	22	Miocene	U ----- M ----- L	Reef limestones Marls; claystones; breccia + tuff intercal. Massive andesite breccias; tuffs; lavas	Shallow marine; increasing continental Vast mud shelfs Island-arc; shelf; coastal lowlands	Active subduction	Shift of magmatic arc to the north Widespread volcano rows in the south
T I A	37	Oligocene	U ----- M ----- L	Lenses of reef limestones; marls; marly clays; sandstones	Strong erosion Global regression Shallow marine Coastal lowland	Re-activated subduction; global plate reorganization	Volcanism absent
R Y	58	Eocene	U ----- M ----- L	Patchy reef limestones; quartz sandstones, quartz conglomerates, siltstones, silica shales, paralic sediments	Stable continental shelf; alluvial plains; coastal lowlands; shallow marine in C-Java	Tectonic quiescence; no subduction (?) Aust-Antarctica separated Drastic slowdown of subduction 54 Ma ago	Volcanism absent on Java
	65	Paleocene		Only fossil melanges exposed	Outer arc basin and ridge; melange wedges	Active subduction of young and hot oceanic lithosphere	Silicic and basic volc.; granitic intrusions in continental crust in the Java Sea area

The Lower Miocene is invariably characterized by massive andesite breccias, tuffs and lavas (Jampang series), attaining thicknesses of up to 2,000 m. In that period a row of volcanoes and volcanic islands emerged, trending approximately along the present-day southern shoreline of Java. The fossil melange and Eocene terrains in Central Java are all intruded by Lower Miocene gabbro/diorite complexes in the form of dykes and plutons. The remaining younger part of the Miocene series exposed on Java is developed as a thick sequence of marls, claystones, incompetent clays, mudstones, dark shales and calcareous clays, with minor thin calcarenite layers and local lenses of reef limestones. Many bituminous zones are reported and these claystones and shales constitute the principal hydrocarbon source rocks. Abundant intercalations of tuffaceous sandstones occur and coarse andesitic breccias are locally present with thicknesses of a few metres. In the northern part of Java monotonous thickly bedded marls and claystones predominate, whilst in the south more variation is present in the form of tuff sandstones, lavas, occasionally lignite seams, polymict breccias and even limestones breccias. The deeper marine areas were present in the north of Java and a row of volcanic islands with alternating shallow marine settings and coastal lowlands on the toes of the volcanoes occurred in the south. Nonetheless, the bulk of the Middle and Upper Miocene series originated in marine environments consisting of vast mud shelfs. However, during the Upper Miocene the sedimentary basins tended to become shallower and continental settings with mixed-marine environments gained in importance. Lenses of reef limestones of Middle- to Upper Miocene age are found near the towns of Bogor and Cirebon are presumably connected chrono-stratigraphically to the extensive Parigi shelf limestones penetrated in many offshore oil wells (Soetomo & Sujanto, 1978). These limestones are overlain by the extensive Cisubuh formation, under the Java Sea, consisting of littoral- and coastal lowland deposits. Massive reef limestones of Middle to Upper Miocene age along the southern coast are limited to the southern coast of Java developed on remnants of the Lower Miocene magmatic arc.

During the Miocene period the magmatic arc shifted to the northern part of Java, as can be inferred from the volcanic rocks in Tegal and Cirebon and the abundant intrusive rocks south of Karawang. In the vicinity of the necks of Upper Miocene volcanoes the proportion of tuffs and tuffaceous sandstones in the marls and claystones becomes significantly higher. The enormous outpouring of volcanic rocks during the Late Oligocene and Lower Miocene, initially from submarine vents and later from emerged volcanoes, must have drastically increased the supercrustal loading on the underlying quasi-continental crust of accreted melanges. It stands to reason that the enormous loading of volcanic rocks and the volcanic cones standing with their feet on the continental shelf may have induced down bending of the continental crust. Hamilton (1979) assumes that the continental edge during the Miocene ran almost parallel to the present-day southern coastline. The overall marine facies of the Miocene rocks may be related to this down bending of the crust. The relation with the deep sedimentary basins north of Java (see Fig. 3.2) remains obscure. Hamilton concludes, based on oil company information, that the structure of basins predates the deposition. However, Padmosukismo and Yahya (1974) argue that block-fault movements have persisted up to Middle Miocene times, implying that the Eocene and Oligocene sediments are affected by faulting. Although the basins may have been created by extensional stresses from 35 to 17 Ma ago, as a result of a slight rotation of the Indo-china peninsula or the effect of stretching by a sinking oceanic slab, it is reasonable to speculate on an origin related to the Lower Miocene magmatic arc in the south. The strike of the axes of the basins, in particular the basins fringing the magmatic arc on Java, trends E-W, thus parallel to the volcanic lines. The widespread intrusion of magma diapirs into the crust beneath Java must inevitably have created volumetric problems for the areas at the adjacent northern side of the magmatic geanticline. The conclusions of Padmosukismo and Yahya support a magmatic related origin. The basins in the vicinity of Kalimantan may have been formed during the Late Cretaceous and Paleocene magmatic activities.

In volcanic island arc settings a complex pattern of basins and ridges is commonly present, bordered by the continental landmass and the magmatic arc. The basins and ridges in the continental basement beneath the Java Sea accord with the general island arc model, even though the basement of the basins is built up of continental crust materials and therefore not a true back-arc basin with an oceanic crust and spreading by upwelling astenospheric materials. This implies that the Java setting must be classified as a continental arc setting.

Summarizing the Miocene scene on Java, it is evident that a row of volcanoes emerged at the edge of the quasi-continental crust during the Lower Miocene. This magmatic arc came into being as a result of reactivated subduction, linked to a major reorganization of plates and movement directions in the Indian Ocean about 35 million years ago. The voluminous volcanic rocks loaded onto the crust may have caused down bending and a vast mud shelf evolved. The provenance areas for the Miocene clayey sediments were located in the continental landmass to the north near Bangka and Belitung and the huge pile of volcanic rocks in the south. During the Miocene the magmatic arc shifted to the north, creating the conditions for massive reef limestone development in southern Java.

The Pliocene series exhibits a fairly analogous geological development of coarse breccias, followed by claystones and marls and overlain by littoral and decreasingly marine deposits, characteristic for the Miocene series. This is particular so in Central Java, since the series in West Java appears to be incomplete. A thick pile of andesitic breccias unconformably overlies the Upper Miocene stage in Central Java and presumably parts of the Upper Miocene deposits have been removed by erosion. The andesitic breccias, the Kumbang Formation in Central Java, reach thicknesses of about 2,000 m. The breccias are overlain by acid greenish crystal tuffs, tuffs, tuffaceous sandstones, locally topped by reef limestones. These crystal tuffs are also present in West Java (Upper Benteng beds). Then follows a fairly thick sequence of monotonous fossiliferous blue claystones, clays and marls, found in both Central- and the eastern part of West Java. Littoral and waterlogged coastal lowland deposits with abundant paralic deposits intercalated with tuff sandstones constitute the last stage and are presumably of an Upper Pliocene age. In West Java the Upper Pliocene stages are predominantly tuffaceous, but point similarly to littoral and coastal lowland environments.

3.2.4 Cycles and patterns in the geological development of Java

Geological developments during the Miocene and Pliocene periods, in which subduction was active, show analogies and sometimes striking similarities in sedimentary basin development and facies. This gives the impression of a chain reaction between interconnected systems, driven by the energy available in the subduction system. A pulse of energy is released from the subduction system and finds its way out through a series of systems, during which the energy is dissipated.

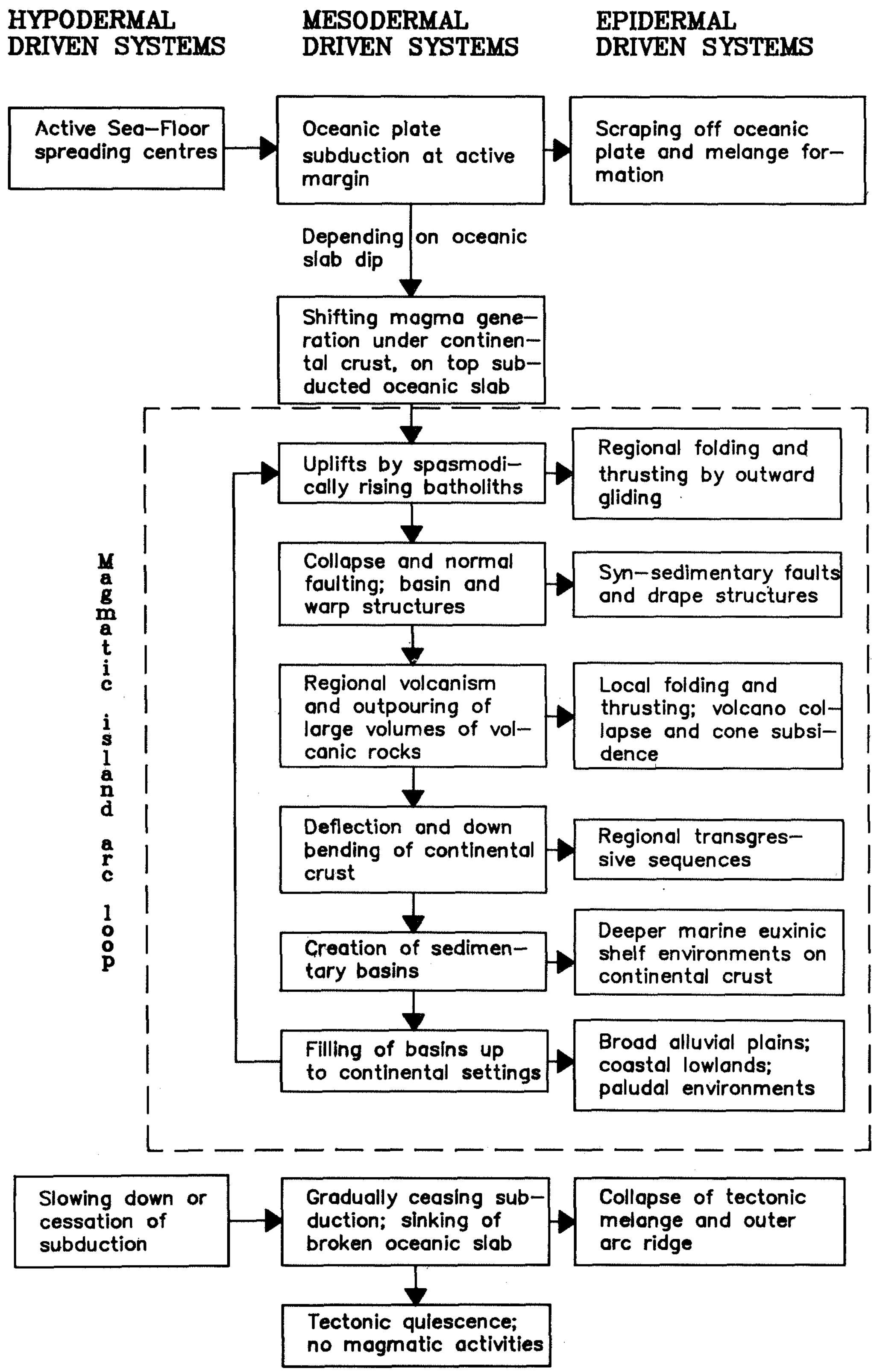


Fig. 3.5 Interlinked earth systems in magmatic island arcs.

Both the Miocene and Pliocene series start with thick sequences of volcanic rocks, partly overlain by transgressive strata of claystones, dark clays and marls. The upper part of the series shows mixed-marine settings with coastal lowlands, paralic environments and littoral sediments and thus a trend towards continental settings.

Fig. 3.5 attempts to summarize the interlinked systems of the magmatic island arc loop found on Java, driven by the magma generation beneath the continental crust. The magma generation constitutes the energy source for the loop. This endogene process heats the top of the subducted oceanic slab and spasmodically releases hot batholiths which ascend and intrude the overlying continental crust, resulting in regionally rising geanticlinals.

During a further phase collapse occurs due to continuous arching of the geanticlinal and deep-seated normal faults are created, forming crustal zones of weakness along which magmas may find their way to the surface. In the event of erupting huge volumes of volcanic rocks, deflection and eventually regional down bending of the overriding quasi-continental plate may take place, thereby creating sedimentary basins. Exogene erosional processes will tend to level the disturbances caused by the endogene forces of uplift. Continuous magma generation or shifting of the magmatic arc in directions parallel to the subduction movements will maintain the magmatic island arc loop. Ceasing subduction activities or changing the dip of the underthrust oceanic slab causes the decay of magma generation and consequently terminates the loop.

3.3 Miocene and Pliocene formations in the kabupatens Tegal and Brebes

3.3.1 Introduction

During field campaigns in 1986 several trips were held to the hilly hinterlands of the kabupatens Brebes and Tegal in the northwestern part of Central Java. Miocene and Pliocene rocks abound in a complex structural framework of northward thrusts and asymmetric folds with E-W trending fold axes. The purpose of the field trips was to investigate the lithology of Neogene rocks underlying the Quaternary sedimentary basins of the coastal lowlands and to gain insight into the Plio-Pleistocene deformation processes. The latter will be described in a subsequent chapter.

3.3.2 Pemali Formation (Lower-Middle Miocene)

The Pemali Formation was named and described by Ter Haar (1935). Due to its clayey character, good quality exposures of this formation are generally hard to find. However, relatively good exposures were located between Banjarharja and the Melahayu reservoir in kabupaten Brebes, about 25 km southwest of the district town Brebes. The Pemali Formation is built up of monotonous bluish grey to light grey marls, clays and calcareous clays. Apart from some dm-thick calcarenite layers, bedding is hardly discernible. Even in the larger and fresh exposures one may completely fail to detect thin layers of some coarser materials or at least any lithological transition from which sedimentary bedding can be inferred. Small Foraminifera are more or less evenly distributed in the marls and are visible even with the naked eye, but the content varies from one exposure to another. The facies and lithological appearance of this formation is remarkably uniform in the kabupatens Brebes and Tegal. Many oil seep localities are indicated on the geological map of south Brebes (Majenang sheet compiled by Kastowo (1975), scale 1:100,000 scale).

A fresh exposure along the river Ci Kabuyutan, south of the town of Banjarharja in kabupaten Brebes, reveals irregular nodules of iron and manganese- oxides and carbonates mostly enveloped by layers of chert. The oxide nodules appear to be syngenetic with a yellow-brown skin of carbonates (rhodochrosite, siderite ?) forming the nucleus for epigenetic chert layers. Even these nodules do not appear to be confined to layers.

The fossiliferous marls and calcareous clays of the Pemali Formation originated in an open marine shelf environment below normal wave base. The interbedded calcarenites may have been formed during storm processes.

3.3.3 Rambatan and Lawak Formations (Middle Miocene)

In kabupaten Tegal, approximately east of an imaginary N-S line through district town Brebes, a mappable lithological unit is found named by Ter Haar (1935) the Rambatan Formation. Stratigraphically the formation is intercalated between the Pemali and Halang Formations, discussed in the next section. That is to say, the geological maps of Kastowo (1975), Djuri (1975) and Condon (1975) assume this formation to be positioned as such. In his original report Ter Haar mentions the lens-like stratigraphic position of this formation and the Lawak Formation. The latter is built up by marls and calcarenite layers and is found occasionally in the Bumiayu area.

The Lawak Formation is exposed in an anticlinal structure near the village Margamukti, 10 km south of Waled in the southern part of kabupaten Brebes. It is developed as monotonous grey-greenish marls with abundant shell fragments and Foraminifera. Burrows and other bioturbation structures are occasionally found. Even in the presence of a dm-bedded calcarenite layer, bedding can hardly be recognized due to flow folding in the anticlinal core.

The Rambatan Formation overlies the Pemali Formation, presumably with an erosion hiatus; concluded by Ter Haar from erosion fragments of Pemali marls at the contact. In the southern parts of the kabupatens Brebes and Cirebon both the Rambatan and Lawak Formations are lacking and Halang beds apparently concordantly overlie the Pemali marls. The Halang Formation becomes considerably thinner east of the imaginary N-S line through Brebes and since the Rambatan Formation resembles much of the Halang Formation, is thought to be a stratigraphically lower member of the Halang Formation.

Excellent exposures are found in Tegal along the river Kali Gung, SW of the reservoir Cacaban. The Rambatan Formation is built up of fossiliferous marine claystones and calcareous clays, intercalated by tuff layers as the Halang Formation. The Halang Formation on the northern side of the reservoir Cacaban shows a similar lithological appearance of m-bedded tuffaceous sandstones in marine shales. However, the tuff and tuffaceous sandstone layers of the Rambatan Formation dominate and may reach thicknesses of more than a metre. The sandstone layers exhibit hydrodynamic sedimentary structures such as small scale cross-bedding and ripple marks. Abundant Foraminifera are clearly visible by eye in the marl and clayey intercalations. Many bioturbation structures are found on top of the tuff and sandstone layers such as crawling traces and burrows. Even rain imprints were found in an exposure southwest of the Cacaban reservoir in kabupaten Tegal. Many exposures are characterized by abundant thin calcite veins cutting through the original bedding planes.

3.3.4 *Halang Formation (Middle-Upper Miocene)*

The Halang Formation with its type locality near the reservoir of Melahayu in kabupaten Brebes, is exposed over vast areas in the Kabupatens Cirebon, Brebes and Tegal. The formation consists of dark clays, bluish-grey claystones, shales and calcareous clays, interstratified with tuff layers and tuffaceous sandstones. Depending on distance to the fossil Upper Miocene eruption centres, located in the northern part of Java, the tuff intercalations may occur sporadically as either cm-bedded thin layers or may constitute the bulk of the section as dm- to m-bedded thick tuffaceous sandstones. The middle and upper parts of the formation, in the south of kabupaten Brebes, may be entirely dominated by volcanic airborne sediments deposited under continental conditions, containing thin paleosols and often charcoal. Lower parts of the formation resemble the Pemali marls. Small lenses of coral limestones, up to a few metres in size, are found near the base. In the absence of tuff intercalations bedding orientation is hard to discern in these plastic clays and claystones, which are heavily sheared in certain zones with intricate meso-scale asymmetric and isoclinal folds. Slickensides and small micro-tectonic offsets are omnipresent. In many outcrops a faint foliation in the clays can be noticed. The distinction from underlying Pemali beds becomes difficult in the absence of tuff layers. Nevertheless, field observations did not indicate an erosion-hiatus at the contact Pemali with Halang, which was also noted by Ter Haar (1935). Foraminifera are again present in the Halang Formation, but are much less abundant than in the Pemali or Rambatan Formations.

In the top of the dm-thick bedded tuff layers and tuffaceous sandstones bioturbation structures can frequently be recognized, in particular crawling traces and burrows. Incidentally, even faint wave ripple marks and mud cracks with thin reddish fossil soil horizons are noticeable, as found in a good exposure near the village Lurahagung along the river Ci Sanggarung. This river coincides with the administrative boundary between kabupaten Brebes and neighbouring Cirebon.

Load structures are often present, from slight bulges to ball-and-pillow structures. Diapirs of the underlying plastic clays are found and may pierce as clastic dykes through the tuff layers, thereby forming thin ridges on top of the latter. An increased content of volcanic ash can be noticed in the claystones just below a tuff layer. Based on these top-and-bottom indicators, the tuff layers are seldom found in an overturned position. The tuff layers frequently alternate with claystones and may even form the bulk of the formation in the vicinity of old eruption centres. Thick m-bedded tuffs and tuffaceous sandstones are found in the vicinity of the Cacaban reservoir, 25 km southeast of the district town of Brebes. Many bedding planes of these tuff layers in this area exhibit wave ripple marks and submarine sliding and slumping features.

A conspicuous feature is the intercalation of andesitic breccias with thicknesses of up to 10 metres. These intercalations appear to be concordant and are overlain by the same marine claystones. These dm-sized breccias appear to have been airborne, fell into the sea and driven into the soft clays; judged from the drag structures and diapiric upbulging at the sides of the andesite blocks.

At Waleddesa, 27 km southeast of the district town Cirebon, the upper block of an upthrust fault consists of Halang calcareous claystones with dm-bedded calcarenite layers. Tuff layers are rare and cm-bedded if present. The bedding plane approaches dips of 90 degrees and is overturned in places. As a result of upthrusting movements of the low-angle fault, to be described in detail later, many slickensides and small offsets are found. This exposure is described here because of the occurrence of calcified fossil drift wood. Large fossil tree trunks and stumps are found in layers. Some stumps give drag structures in underlying thin tuff layers, as if the trunks and stumps had penetrated by their weight into the soft calcareous clays. However, subaerial deposits were not found, implying that the tree trunks must have been washed in by rivers. Floating in the open sea, the tree remains were gradually decomposed and the void and vugs presumably filled with carbonate cement, upon which they sank to the sea bottom and penetrated the soft high porosity muds. Some much less spectacular silicified wood remains were found in other exposures of the Halang Formation in northern parts of the Tertiary terrains.

Because of the complex geological structure with upthrusts and overthrust, it remains difficult to determine the stratigraphic position of the sedimentary features described above. In general the dark claystones with infrequent tuff intercalations are found in the lower parts of the Halang Formation. In the upper parts local reef limestones are known to occur and the tuff layers become more abundant.

The major part of the Halang Formation, in particular the lower and middle part have been deposited below wave base in an open marine environment. However, the abundance of crawling traces on the tuff layers exclude an euxinic environment devoid of animals. The tuff and tuffaceous sandstone layers are rarely characterized by graded bedding. Sorting of the airborne volcanic materials already took place already during air transport. The upper part of the Halang Formation in which reef limestones and tuff layers with ripple marks occur point to more shallow conditions. The reef limestones and in particular m-bedded fossiliferous limestones are much more abundant in the area of Tegal as indicated on the geological map by Djuri (1975), but are also found in the Cirebon Kromong complex and the problematic Cisande reef (discussed by Van Bemmelen, 1949, p:650) at the boundary of kabupatens Cirebon and Brebes. These reef limestones presumably belong to the extensive shelf carbonates developed towards the north, which includes the Parigi formation as found in oil wells beneath the present coastal lowlands (Soetomo & Sujanto, 1978), and may indicate the southernmost limit of carbonate deposition.

Contrasting with the open marine mud facies of the Halang Formation is the littoral mixed sand-mud facies of the Rambatan Formation, representing the shallower flanks of the Halang basin which were converted into open marine environments. The Rambatan Formation is a subregional phenomenon only, whereas the Halang Formation is exposed over vast areas.

Summarizing the Miocene series it can be said that going upward in the series a general trend of shallower marine environments is noticeable; from the monotonous Pemali Formation with abundant bituminous zones towards the relatively shallower facies of the Halang Formation with occasional bioturbation, ripple marks and incidental faint fossil soil horizons. Important structural highs were present in Miocene times.

3.3.5 Kumbang Formation (Upper Miocene-Lower Pliocene)

A thick sequence of andesitic lavas and breccias is found in the southern part of kabupaten Brebes. Kastowo (1975) estimates a thickness of 2,400 m and Van Bemmelen (1949) assigns a Mio-Pliocene age to these Kumbang breccias. Breccias overlying the Halang claystones are separated by an angular unconformity. The migration of the magmatic arc in Miocene times from a position at the southern coast of present-day Java to a northward position resulted in folding and thrusting of the Halang claystones. Presumably the area partly emerged before the Kumbang lavas and breccias were poured out. The occurrence of reef limestones in the upper part of the Halang Formation may reflect uplifts due to a shifting geanticline.

The Kumbang Breccias near Banjarharja consist of dm-sized fragments, completely unsorted and with a matrix of light coloured tuffs. Many andesite fragments reveal lava flow structures. The Kumbang Formation appears to be an excellent field indicator for determination of the underlying rocks. To distinguish between the Pemali and Halang Formations is often a problem in the field when they are developed as dark to bluish-grey clays and barren of tuff intercalations. The presence of Kumbang Breccias in these cases confirms the underlying rocks to belong to the Halang Formation.

3.3.6 Tapak Formation (Lower-Middle Pliocene)

A good section of the Tapak Formation is present in the hill of Karangbale, about 7.5 km east of Banjarharja. Well-bedded light coloured acid crystal tuffs are exposed with bed thicknesses from 10 to 50 cm. Marls become gradually intercalated stratigraphically upwards and the top of the hill is capped by partly recrystallized reef limestones. The limestones are karstified, exhibiting vugs and some caverns.

The karstification process presumably took place during the Pleistocene, judging from the angle between the bedding plane dipping about 20 degrees to the north and the almost horizontal orientation of the cavern floors and karst horizons.

Along the river Kali Pemali, flowing towards the district Brebes, the Tapak Formation exhibits the same lithology of crystal tuffs. However, thick reddish-brown fossil soil horizons are present indicating weathering of the tuffs in hot humid climates.

3.3.7 Kalibiuk Formation (Middle Pliocene)

Pliocene rocks outcrop on the southern border of the coastal lowlands in kabupaten Tegal, between the district towns of Tegal and Pemalang. On his geological map of the Purwokerto and Tegal quadrangles Djuri (1975) maps these rocks as the Tapak Formation and describes the lithology as greenish coarse grained sandstones and conglomerates. This description is not confirmed by the exposed Pliocene rocks, which consist mainly of clays and claystones. Even the description of Djuri for the Tapak Formation is not in accordance with the fairly uniform lithology of light coloured acid crystal tuffs. A number of surveys have been carried in the Pliocene rocks to investigate the ambiguities between the geological map description and the rocks in the field.

The river Kali Rambut (see Fig. 4.1 for location), draining a part of the northern slope of the Slamet volcano and flowing just west of Pemalang, is incised in the Pliocene rocks rendering good exposures. Near the villages Gongseng and Cipero steeply northward dipping cm- to dm-bedded claystones and marls are exposed. The claystones are light-grey to dark-grey coloured. Intercalations occur of calcarenite layers, tuff layers and in places almost m-bedded tuff sandstones. The claystones contain many small Foraminifera and abundant Mollusca shells. Bioturbation is omnipresent in the tuff layers consisting also of crawling tracks and burrowing activities. Load casts and small scale clay diapirism provide the clues to determine top and bottom.

The lithology of this section along the river Kali Rambut correlates exactly with the Kalibiuk Formation described by Ter Haar (1935), consisting of clay marls with sandstone intercalations and rich in mollusca. Marine claystones and marls were also encountered in the southern part of the exposed Pliocene terrain. Sections were surveyed north of the reservoir Cacaban, along the river Kali Domba and from the villages Dukuhranda and Karangmalang in the south. All confirmed the presence of monotonous bluish-grey marine claystones with shell fragments and occasionally a sandy intercalation, the typical facies of the Kalibiuk Formation. The description on the map of Djuri (1975) is thus considered to be incorrect.

3.3.8 Kaliglagah/Cijulang Formation (Upper Pliocene)

Outcrops of this Upper Pliocene Formation, as described first by Ter Haar (1935), were investigated near Banjarharja and in the Pliocene terrains in the central part of kabupaten Tegal. The Pliocene hills bordering the coastal lowlands in Tegal are designated on the geological map of Djuri (1975) as the Tapak Formation. Several surveys in these hills disclosed a lithology of homogeneous mottled light-grey clays without any bedding plane. Pulverizing the clays by hand reveals the presence of angular fine pebbles, whereas breaking a hand specimen of the clays results in a conspicuous lustrous irregular plane of failure. Occasionally wood, leaf remains and charcoal are found. Some red-brown coloured coarse sandstones and gravel layers, containing wood remains and reaching thicknesses of up to 2 or 3 m are intercalated in the structureless clays. Tuff layers may occur also. Certain zones in the clays contain cm-sized flakes of gypsum or even sulphur and are related to coastal swamp deposits of black clays with much carbonaceous matter and wood remains. Further towards the south the marine clays and marls of the Kalibiuk Formation appear.

In the Pliocene terrains near Banjarharja a similar lithology was found consisting of these deeply weathered structureless clays with coastal swamp deposits and thin lignite seams. Blue-grey dm- to m-bedded tuff layers are present, cemented by calcium carbonate. The tuffs obviously fell into the sea and contain many fractured shell remains at the bottom. Presumably the shells were fractured under the load of the tuff layers. These blue-grey tuffs are overlain by red-brown coloured conglomerates and breccias, which resemble debris flows, perhaps resulting from lahar flows. Tuffs deposited on the shallow sea floor consisting of calcareous muds and clays have developed load cast structures up to ball-and-pillow size.

Judging from the lithology of the Kaliglagah Formation, the impression is gained of swampy coastal lowlands with deeply weathered clays, mainly floodplain clays and weathered volcanic ash. Both the coastal lowlands and the adjacent shallow sea were frequently covered by pyroclastic rocks, originating either directly from the eruption centres or transported and re-deposited by lahar flows and fluvial action. A continuation of the Kaliglagah Formation is found in offshore oil wells, known as the continental Cisubuh formation ranging from Late Miocene to Plio-Pleistocene.

3.3.9 Concluding remarks on the Mio-Pliocene formations in Tegal and Brebes.

Lithological developments of the Miocene and Pliocene series found in Tegal and Brebes accord with the facies development elaborated in Table 3.2. Although the base of the Miocene is not exposed, both series start with thick sequences of volcanic breccias, unconformably overlying older formations. The middle parts of the series are characterized by vast open marine shelf environments, albeit interrupted by basement highs. In the upper parts of the series tendencies are noticeable, especially in the Pliocene series, towards shallow marine and coastal lowland settings.

IV. THE PLEISTOCENE EMERGENCE OF JAVA AND MAJOR GEOLOGIC EVENTS

4.1 Introduction

The Pleistocene has been the most decisive geological time span for determining the present-day shape of the island of Java. The epoch is characterized by widespread volcanism which occurred within a belt of approximately 50 to 75 km wide and the major regional and local geological deformations were produced during this time span. Contrary to the Upper Tertiary marine settings with rows of volcanoes surrounded by shallow seas, the outset of the Pleistocene marks the beginning of the terrestrial setting known today. Final emergence resulted from not only the huge volumes of Pleistocene volcanic rocks but also major uplifts along the longitudinal axis of the island.

During the Pleistocene epoch the sedimentary basins beneath the present-day northern coastal lowlands were formed and filled with erosion products from the emerged hinterland. The major part of this sediment pile in the basins was deposited during the Pleistocene and, conceivably, regional geological events during this epoch must have influenced the general erosion/transport/accumulation (ETA systems, Engelen & Venneker, 1988) conditions.

The most outstanding feature of the Pleistocene as viewed on a global scale is the rather high amplitude and frequency of climatic oscillations. Lowe & Walker (1984) mention temperature fluctuations of more than 15^{0}C in certain parts of the world and further observe that at least twenty glacial-interglacial cycles can be traced during the Quaternary period. Sea level fluctuations due to water storage in the ice caps may have reached 150 m. The climatic changes had large impacts on a variety of geological processes, in particular erosional/transport/accumulation systems (ETA systems). Evidence has gradually become available which indicates that even the low-latitude regions have apparently not escaped the effects of climatic changes. Morphological investigations in low-latitude regions in Africa and South America (Beaudet et al., 1981; Seuffert, 1978; Besler, 1985; Heine, 1981; Tricart, 1965; Verstappen, 1974, 1980 and Wirthmann, 1985) have shown that climatic phases of aridity were alternating with pluvials.

In this thesis it will be shown, contrary to the long held view, that important climatic changes have also taken place on Java during the Pleistocene and have influenced ETA systems.

4.2 Pleistocene geological evolution of North Java

4.2.1 Introduction

A reconstruction of major events during the Pleistocene epoch and the effects upon sedimentary patterns, based on existing literature, remains a difficult task. Many publications are contradictory with respect to the major volcanic events and regional unconformities. Van Bemmelen (1941) in his explanatory notes to the geological map sheets of Semarang and Ungaran proposes a vigorous revival of volcanism in the Lower Pleistocene, during which the Plio-Pleistocene Damar beds were deposited with apparently conformable contacts between the members. Ter Haar (1935) stresses a similar type of deposition for the tuffaceous Lower Pleistocene Mengger beds in Tegal and Brebes, lying conformably over the Late Pliocene Kaliglagah beds. Van der Linden (1978), based on his study of fossil soil profiles in the southern part of the Serayu valley, is inclined to the opinion that the revival of volcanism started in Middle Pleistocene times. Sutarso and Padmosukismo (1978), reporting on the occurrence of hydrocarbons in the northeast Java basin (from Semarang to the island Madura), argue that the break between the Late Pliocene and Pleistocene is widespread and marks epirogenic movements and severe erosion. Smit Sibinga (1949), in his essay on Pleistocene eustasy and glacial chronology in Java and Sumatra, visualizes a broad submarine geo-synclinal basin in North Java stretching from west to east and bounded in the south by a row of islands constituting the geanticlinal ridge of South Java.

Timings of the folding phases are equally controversial. Van Bemmelen (1941, 1949) and Ter Haąr (1935) assign a Middle Pleistocene age to major phase of deformation, whereas Sutarso and Padmosukismo (1978) mention a Middle to Upper Pleistocene age. Hamilton (1979) theorizes that folding in the major basins of West- and East Java began in the Middle Miocene, that folds have grown during sedimentation and that no distinct brief periods of folding have occurred. Speelman (1978) assigns a Middle Pleistocene age to the major deformations of the north Serayu Mountains in Central Java.

From the foregoing it will be evident that a general consensus is still lacking among the various scholars with respect to major geological events during the Pleistocene. In order to shed light upon major events, viewed against the background of specific island arc tectonic loops, a correlation will be made between the various Pleistocene stages in North Java, their degree of deformation and stratigraphic contacts. Fieldwork by the present author in the hilly Tertiary areas south of the coastal lowlands revealed new important data, so far not mentioned in any report of the Geological Survey of Bandung, which is thought to be important in reconstructing the Pleistocene.

4.2.2 Major Pleistocene stages in North Java

Based on the available geological sheets of the northern part of Java and the pre-war reports of the Geological Survey of Bandung, in particular Van Bemmelen (1934, 1941) and Ter Haar (1935), a framework (see Table 4.1) is constructed of the major exposed Pleistocene stages in a belt stretching from Semarang to Cianjur and Karawang.

A correlation of mappable volcanic units on the various map sheets appears to be a difficult task. The stratigraphic position of volcanic units is designated by confusing connotations such as 'folded breccias', 'young', 'old', 'older' and 'oldest' volcanics without specific formation names, making any correlation between adjacent sheets difficult. However, in Central Java more consistent formation names (viz. Damar, Notopuro, Ligung, Gintung and Linggopodo) are given to the volcanic series, though sound age determinations are lacking. The 'oldest' and 'older' volcanics are usually attributed to the Lower Pleistocene, the 'old' volcanics to the Middle or Middle-Upper Pleistocene and 'young' as Late Pleistocene-Holocene. Speelman (1978) reports an isotopic age determination of 0.87 ± 0.1 million years for a rock specimen belonging to the Notopuro layers found in the north Serayu Mountains and assigns this age to the Middle Pleistocene. The boundaries of the Pleistocene stages in Table 4.1 are based on correlation with similar stages in the Sangiran area along the river Bengawan Solo southeast of Semarang.

Table 4.1 Major exposed Pleistocene stages in North Java.

EPOCH	AGE	REGIONS					Major geological events
		Semarang/ Pekalongan	Tegal/ Brebes/ Majenang	Cirebon/ Indramayu	Subang/ Bandung	Karawang/ Cianjur	
HOLOCENE		Outward building northern coastal lowland deposits marine clay blankets, delta deposits, floodplain clays					Starting cone collapses and foot folding
HOLOCENE - PLEISTOCENE	UPPER	Young unfolded volcanic series of Sumbing and Dieng volcanoes	Young unfolded volcanic series of Slamet volcano	Young unfolded volcanic series of Ciremai volcano	Young unfolded volcanic series of Prahu volcano	Young unfolded volcanic series of Prahu and Gede volcano	Volcanic fans Regional reactivated volcanism along existing vents Uplifting Marine terraces in Tegal Local collapses of cones warping and folding of cone feet
		/\/\/\/\/\	/\/\/\/\/	/\/\/\/\/	/\/\/\/\/	/\/\/\/\/	
PLEISTOCENE	MIDDLE	Notopuro layers folded volcanics of old Dieng and Ungaran volcanoes	Linggopodo layers folded volcanics of old Slamet	Old volcanic folded layers of Ciremai volcano	Old volcanic folded layers of Sunda volcano	Old volcanics of Gede volcano ? (not exposed ?)	Regional piercing of magmas with widespread volcanism
		/\/\/\/\/\	/\/\/\/\/	--?---?--	--?---?--	--?---?--	
		Upper Damar layers (continental volcanics, fluvial deposits)	Gintung layers (continental volcanics fluvial deposits)	Gintung layers in eastern part only ?	? ?	? ?	Regional collapse along deep-seated E-W faults; formation of Bandung/Garut basins
		---------	---------	--?---?--	--?---?--	--?---?--	Regional uplifts by ascending magmas
	LOWER	Middle Damar layers (volcanic breccias)	Mengger layers (tuffs)	Volcanic series of Kromong complex	Tambakan layers (volcanics, fluvial, paralic)	Tambakan layers (continental volc.) Oldest volc. ?	Local volcanism
-	-	---------	---------	/\/\/\/\/	/\/\/\/\/	/\/\/\/\/	Northward glidings and thrusts
PLIO		Lower Damar beds	Kaliglagah beds	Ciherang/ Cijulang	Citalang	Citalang	
		Vast coastal lowland settings with fluvial, deltaic and shallow marine deposits, abrupt facies changes					Uplifting

Orchiston & Siesser (1982) and Sartono (1984) review the results of various dating methods, including radiometric dating, for the formations in the Sangiran area (structural dome on the NW slope of the Lawu volcano near the town of Solo) with hominid bearing horizons. Despite the number of sophisticated dating methods applied to the rocks exposed in the Sangiran dome and nearby Trinil area, a widely accepted Pleistocene stratigraphy framework is still lacking. Many workers are engaged in heated debates on Pleistocene stratigraphy and each new result of radiometric- or paleontological datings seems to arouse greater controversies. Nevertheless, many authors propose a preliminary chronostratigraphy for the Pleistocene which has been adopted here for reasons of completeness.

The Pleistocene volcanics are loaded on Late Pliocene rocks such as the Kaliglagah and Citalang Formations, with a rather uniform facies throughout the area consisting of coastal lowland sediments with abrupt facies changes from marine, deltaic to purely fluvial with intercalations of tuffaceous beds. The paleogeography at the end of the Pliocene may have resembled the present-day setting at the eastern coast of Sumatra; thus vast and extended marshy coastal lowlands with low relief areas emerging in the southern parts of Java. These Late Pliocene-Early Pleistocene coastal lowlands may have stretched far onto the Sunda shelf. North of the coastal lowlands a shallow sea must have existed in Late Pliocene times fringing the Sunda land area of the Karimunjawa arch in this central part of the present Java Sea.

In the Sunda sub-basin, the northwest Java sub-basin and the offshore northwest Java sub-basin, the Upper Pliocene Cisubuh Formation is developed as unconsolidated claystones with calcareous streaks passing into the uppermost carbonaceous shale and sandstone member, thus indicating the last regressive cycle of Tertiary sedimentation (Soetomo & Sujanto, 1978).

Ter Haar (1935) describes a location in the upper part of the Kaliglagah Formation in the southern part of Brebes near the river Kali Pemali, at about 28.5 km NE of the town of Majenang, with many vertebrate remains. In the years 1925 to 1930 systematic excavations were carried out which yielded bones of large mammalia such as Hippotamus, Mastodon and Stegodon. Ter Haar argues that these vertebrate beds situated about 100 m below the top of the Kaliglagah Formation, which is conformably overlain by the Mengger layers, might be even of Early Pleistocene age. The location in the river Kali Glagah mentioned by Ter Haar was visited by the present author during the dry season. The layers from which the vertebrate remains were derived consist of flood plain clays with plant and leaf remains similar to those found in the Kaliglagah Formation exposed along the river Kali Semedo. Some specimens exhibited in the institute of the Geological survey of Indonesia in Bandung are thought to date from the transition Plio-Pleistocene to Early Pleistocene.

The significance of this exposure, however, is the conformable contact between the Kaliglagah and the overlying Mengger tuffaceous layers. Similar conformable contacts were also reported by Van Bemmelen (1941) for the Lower and Middle Damar beds. The Lower Damar beds are lithologically similar to the Kaliglagah Formation. Towards West Java an angular unconformity becomes clearly noticeable, particularly in the Subang-Bandung regions and beyond. However in Cirebon a major E-W trending northward thrust fault is easily recognizable near Waled (at the boundary between the kabupatens Cirebon and Brebes) unconformably overlain by the Gintung layers. The thrust structure continues under the huge cone of Ciremai volcano and the fault reappears west of the Kromong complex. Both Ter Haar and Van Bemmelen stress the conformable contact in Tegal-Majenang and in Semarang-Pekalongan between the Mengger-Gintung layers and the Middle-Upper Dámar layers, respectively.

In the Subang-Bandung region, the Tambakan beds consist of volcanics and erosion products of the uplifted Late Pliocene strata. This implies a significant contrast between Central- and West Java with respect to the contacts of Pleistocene volcanics with the underlying Late Tertiary strata. These tectonic discrepancies between West- and Central Java will be further discussed in section 4.2.4. The northward thrusts must have taken place at the Pliocene-Pleistocene boundary, resulting from outward gliding against an uplifted area in the south. The uplifts may have been confined mainly to West Java, but it is presumably the thicker pile of Tertiary sediments in the West Java basins which led to more pronounced thrust structures. The remains of the Kromong complex, a deeply eroded volcanic ruin in kabupâten Cirebon, do not allow determination of contacts with the underlying Pliocene Kaliwangu clays and overlying volcanics of the old Ciremai volcano. Thrust movements at the end of the Pliocene suggest an angular conformity with the underlying Kaliwangu beds.

Contrary to the northward thrusting which increases to the west, the Lower Pleistocene volcanic activity in Central Java appears to increase towards the east. Whilst the Tambakan beds are mainly continental deposits, Van Bemmelen (1941) mentions a vigorous revival of volcanic activity in the Semarang-Pekalongan sector. The stratigraphic equivalent of the Upper Damar layers and Gintung layers in West Java remains obscure. The same applies to the contact of the Tambakan layers with the overlying old volcanics. The angular unconformity between the Upper Damar- and Gintung layers with the overlying old volcanics of the Slamet and Dieng volcanoes is evident in Central Java, but in Cirebon the contact is not exposed.

Several exposures of the Gintung Formation have been studied in the western part of kabupaten Brebes and in the eastern part of kabupaten Cirebon. The Gintung Formation near the river Ci Sanggarung at the villages Legok, Waleddesa and Cibendung show sub-horizontal to slightly N-NE dipping beds of mainly fluvial redeposited volcanic materials. Sandstones dm-bedded, finely laminated and cross-bedded and dm- to m-bedded conglomerate layers intercalated with lahar flows make up the bulk of the formation in these exposures. Colours vary from light grey to reddish weathering zones. A quarry at Legok exposes the fluvial facies of the Gintung Formation with airborne ash and lapilli layers and lacustrine intercalations. The volcanic materials appear to have been transported by sheet wash. The bedding dips slightly to the N and NE. Northwest of the town Sindanglaut in kabupaten Cirebon near the dam in the river Ci Wado similar fluvially redeposited volcanic materials are found, including black flood plain clays with plant remains. Except for some NW-SE directed graben structures, due to the diapiric outward squeezing of Kalibiuk Formation plastic marine clays from beneath the toes of the Ciremai volcano, the original orientation of the Gintung layers is sub-horizontal to slightly dipping to the NE. From the dipping of the Gintung layers in the kabupatens Brebes and Cirebon a conformable contact may be expected with the overlying old volcanics of the Ciremai volcano.

The 'old volcanics' of Middle-Upper Pleistocene age are omnipresent in the mentioned regions and constitute the magmatic backbone of Java. Except for the area west of Cianjur, in which the old volcanics of the Gede volcano are not exposed, the Middle tô Upper Pleistocene volcanic rocks outcrop from beneath covers of younger volcanics in all the investigated regions. A conspicuous feature of the Java volcanoes is the tendency to tectonic collapse due to severe foundation problems of the huge cones resting on ductile clayey Tertiary formations. The ductile rocks under the cones are squeezed radially outwards giving rise to upbulging volcano toes, as evidenced by the dome structures of Sangiran and Gemolong, in the valley of the river Bengawan Solo (Central Java). In later stages parts of the cones may glide outwards in triangular sectors. The geological maps indicate that all larger volcanoes of the old volcanic series suffered from cone collapse, leading to folding and outward thrusting of strata at the toes of the volcanoes. Deformation structures around the old volcanic cones decrease remarkably with increasing distance.

The younger volcanics are mostly built up in the vicinity of the old eruption centres and cap the older calderas or ring-fault bounded collapse structures. In some cases the young volcanic cone mantles are obviously influenced by existing older fault structures. Generally, due to profound geologic events of cone collapse and subsidence, the contacts of the young volcanics with the older ones show an angular unconformity.

Summarizing the main Pleistocene stages in the northern part of Central- and West Java, it can be said that more or less conformable contacts exist between the Lower and Lower-Middle Pleistocene stages and the Pliocene strata in Central Java. Towards West Java northward directed thrust movements become evident and a distinct angular unconformity is noticeable in West Java at the Plio-Pleistocene boundary. Whilst the Lower Pleistocene is characterized by vigorous volcanism in Central Java, relatively quiet volcanic activities are found in the Lower Pleistocene for West Java. The 'old volcanics' are omnipresent in the studied region and can be considered as the major phase in the emergence of Java. Collapse of the old volcanic cones has led to important deformations in radial patterns around the cones. These collapsed, faulted and folded toe structures of the old volcanoes are capped and partly covered by the younger volcanics at the Pleistocene-Holocene boundary.

4.2.3 The stratigraphic significance of some Pleistocene rock sections

In this section several outcrops of Pleistocene rocks will be discussed which are thought to be of paramount importance for the reconstruction of the major geological events. During surveys in the Tertiary hills in the eastern part of kabupaten Tegal, 13 km SE of the town Pemalang, pieces of beach rock colluvium were accidentally found in isolated places in a brook and in ploughed fields. By climbing the Tertiary hills east of Gunung Tirem, near the hamlet Semedo, from the piedmont plain of the coastal lowlands, more beach rocks with many shell accumulations were found in the brook and numerous pieces on the ploughed northern hill side (see Fig. 4.1). However, in situ material the northern part of the Tertiary hills consists of black flood plain clays, mottled with leaf and plant remains belonging to the Kaliglagah Formation. Coastal swamp deposits can frequently be recognized in the clays with gypsum crystals and the bright yellow coloured mineral jarosite. On the geological map (sheet Purwokerto-Tegal, by Djuri, 1975) these rocks are erroneously mapped as the Tapak Formation. The geological map of Fig. 4.1 shows revisions to this map of Djuri. Following the brook towards the south, minor intercalations occur of brown coloured fluvial cross-bedded sandstones and conglomerates with a total bedding thickness of about one metre. The bottom contact of the sandstones with the black flood plain clays shows an erosional contact. The sandstone beds dip 60 degrees in a NE direction, decreasing to about 25 degrees further south. Intercalations of tuffaceous sandstones near the northern rim of the Pliocene hills in more westerly located outcrops, south of Karangmalang, show NE dips of 85 degrees. The sandstones and conglomerates contain calcified and silicified wood trunks and remains. Irregularly distributed calcium carbonate-cemented sandstones are derived from these sandstone layers, presently found in the brook alluvium.

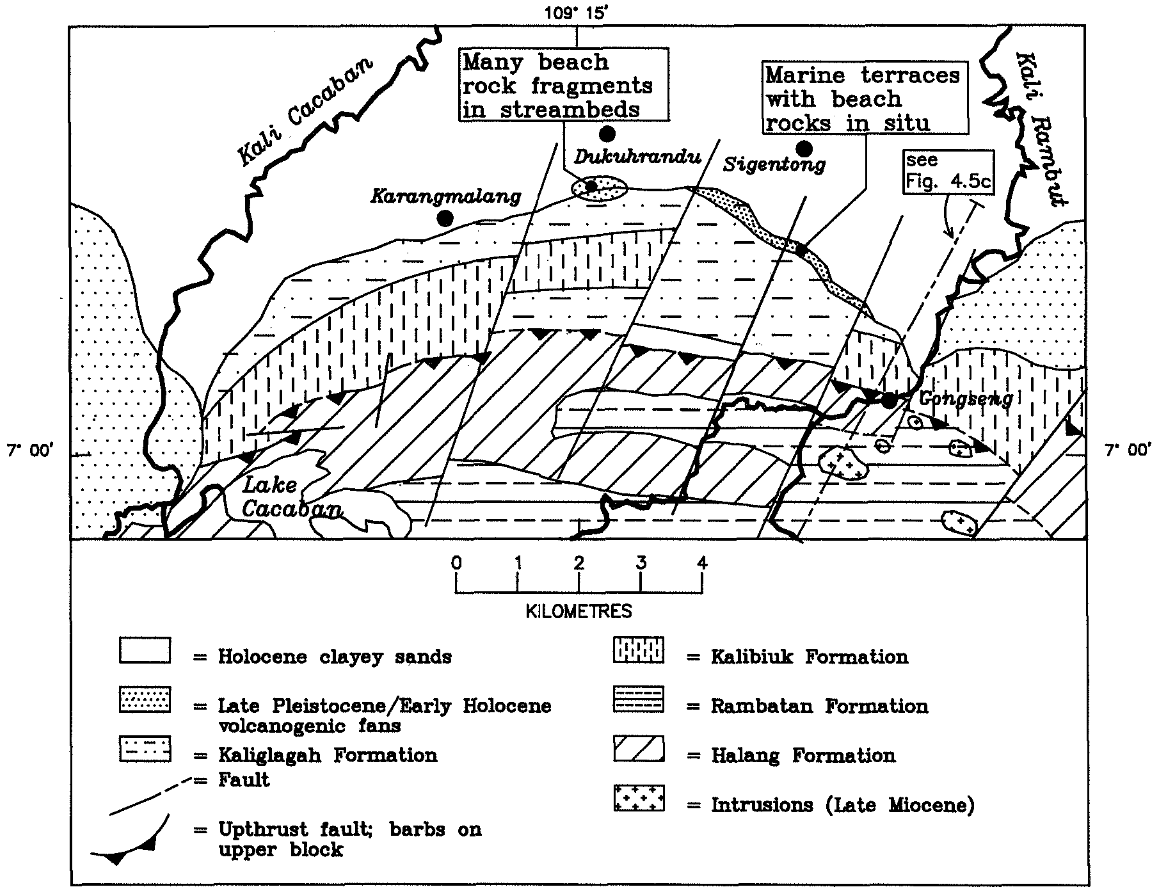
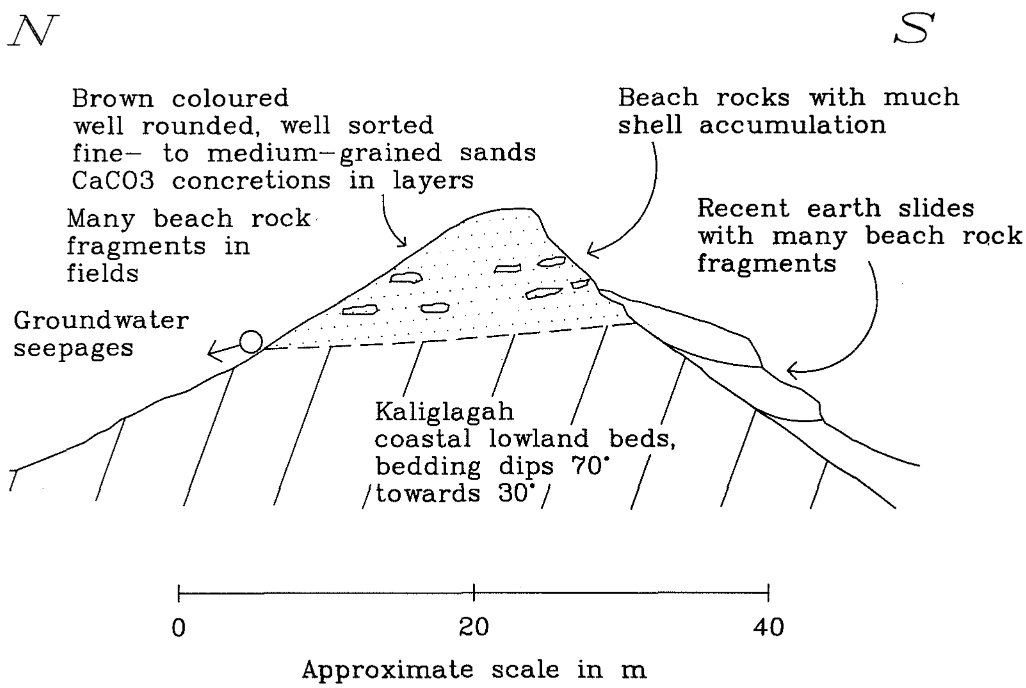


Fig. 4.1 Location map of the Pleistocene marine terraces.

The beach rock outcrops are found as isolated remnants discordant upon the Kaliglagah clays. The best outcrop is found just behind the north facing Pliocene hills, at the eastern side of the stream where an earthslide has exposed a vertical section (see Fig. 4.2a, upper sketch). Beach rock fragments with very dense shell accumulations are found scattered in the slumped earthmass. About 5 m below the hill top beach rocks are found in situ as irregular 5 to 15 cm-thick lenses, forming consistent horizons dipping slightly to the north. The internal structure of the lenses shows low-angle laminations and cross-bedding. The matrix of the beach rock comprises fine- to medium-grained sands with widely varying shell fragment contents the grains of the brownish coloured beach sands being well cemented by calcium carbonate. Bioturbation structures and scour and tool marks are omnipresent in these beach rocks.

The bulk of the section consists of brown, well rounded and well sorted sands, mostly fine- to medium-grained and occasionally slightly clayey, and with small broken shell fragments. The mineral content of the sands indicates a volcanic origin.



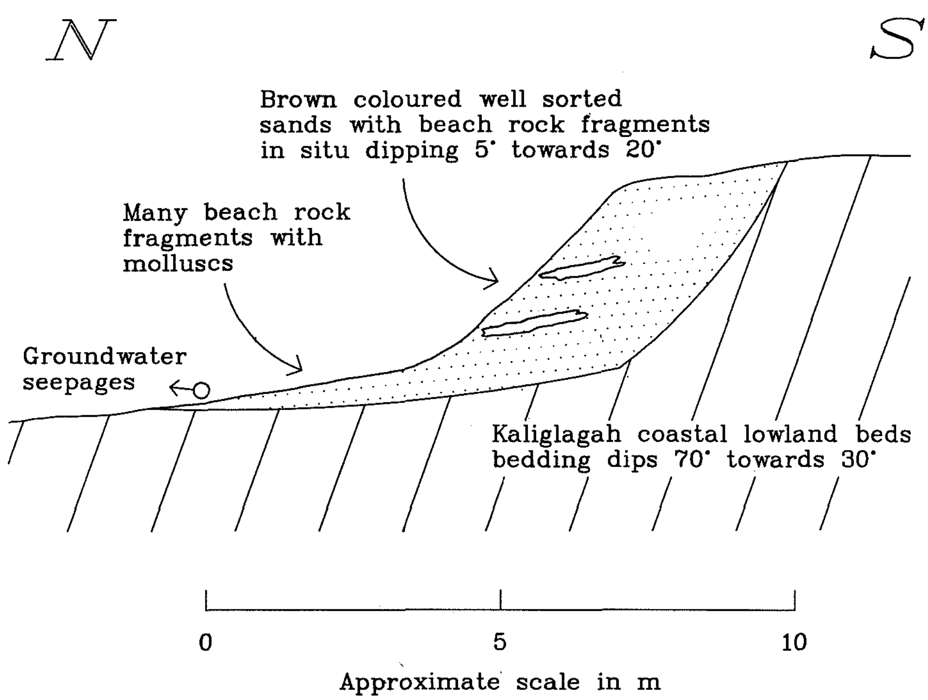


Fig. 4.2ab Field sketches of the Pleistocene fossil shoreline deposits south of village of Sigentong; see Fig. 4.1.

Sedimentary structures are difficult to recognize in the brown sands. Pedogenetic calcium carbonate concretions of about a centimetre diameter occur as faint white horizons. Some fossils were collected from the sands in which bedding is discernible as thin clayey horizons. These horizons consist of clay lumps which are obviously derived from the Upper Pliocene Kaliglagah Formation by marine abrasion. The same can be said of the flat and extremely smooth cm-sized pebbles in the brown sands, also derived from infrequent dm-bedded sandstones and conglomerates in the Kaliglagah coastal lowland clays. Nearby outcrops in the Kaliglagah clays reveal these steeply northward dipping sandstones and conglomerate layers in situ with the same Fe/Mn-stained pebbles, although not as smooth as those found in the beach rock outcrops. Nevertheless, the pebbles undoubtedly originated in the Kaliglagah Formation, with further smoothing and polishing taking place along the shoreline associated with the beach rocks.

In a westerly direction along the same height contour, beach rock fragments are easily found in the ploughed fields. Good exposures with beach rocks in situ exist at locations where the terraces with shoreline deposits have been eroded by streams from the hinterland.

Based on the good sorting and roundness of the grains the brown sands are interpreted here as beach- and eolian sands from a setting of backshore to shoreface. Fossil remains in horizons and some laminations also point to a beach deposit cemented by calcium carbonate[1]. The upper sketch in Fig. 4.2a depicts the general situation and the stratigraphic relation with the underlying folded Late Pliocene clays. It is interesting to note that small groundwater seepages occur at approximately the base of the shoreline deposits. The topographical altitude of these shoreline deposits is 40-50 m above M.S.L. Following this height contour a further relict of these shoreline deposits is found about 300 m to the east. Similar brown eolian sands are found with contact against the Kaliglagah clays (see Fig. 4.2b, lower sketch), and although beach rocks are in the minority they show the same slightly northward dip. Abundant shell accumulations are not found in these beach rocks, but crawling tracks instead. In the fields between this outcrop and the previous one beach rock fragments with many mollusca shells were again found. In this second outcrop similar groundwater seepages occur at the contact with Kaliglagah clays. Further to the east beach rocks are found only as colluvial fragments in the newly ploughed fields.

A planation terrace is noticeable at this altitude on the northward facing hills. The small flat and extremely smooth beach gravels found in the first exposure are also present. Looking further east a similar planation terrace is evident in the Upper Damar layers.

The geological map of Djuri (1975) marks a mollusca location near Semedo which presumably corresponds with the shell containing beach rocks.

The significance of these shoreline deposits is their unconformable contact with the underlying folded Kaliglagah clays. In a previous section it was argued that northward thrusting movements which occurred in West Java apparently did not occur in this part of Central Java. This implies that the main folding of the Kaliglagah clays, with their beds be-

1 Beach rock samples from these exposures were kindly examined by paleontologist Dr. C. Beets (1988). In his written personal communication, he concludes that the samples can indeed be described as 'beach rock', being deposited in the highest zones of the inter-tidal zone. A mollusca fauna is identified, containing such species as Ostrea sp., Tellina-like shells, Arca sp., Dentalium-like shells, Turritella sp. and abundant small Venus shells, known as V. Berauensis Beets, 1950. Despite the abundance of mollusca shells dating of the deposits appears to be very difficult. To decide whether the deposit has a Pliocene or Pleistocene age is complicated by the fact that the fauna occurs both in Upper Tertiary and recent sediments. Beets finally remarks that the sediment looks 'very young' and does not resemble the Pliocene deposits on Java.

coming steeper to the north (and even overturned as found in the river Kali Rambutan north of Gongseng-Cipero), is connected to the collapse and subsequent foot folding of the old Slamet volcano. Thus the shoreline must have been formed after the foot folding and outward gliding against the old Slamet volcano. As will be touched upon in further sections there is enough evidence, such as backward rotated Holocene gravels, to assume that regional outward gliding movements occurred even during the Holocene. Hopley (1986, in Van Der Plassche, 1986) pointed out that the uppermost level of beach rock cementation should be horizontal and not sloping. The dip of 5 degrees towards 40 of beach rock layers as measured in the outcrops is fairly consistent and may indicate tectonic movements after deposition. The present altitude above the piedmont plain proves that the deposits must be older than Holocene, since it appears that after deglaciation model studies based on a spherical viscoelastic earth by Clark et al. (1978) eustatic sea levels have not exceeded present-day levels (Kidson, 1986 in Van Der Plassche, 1986)[2]. Walcott (1972) advanced the idea that areas at great distance from glaciated regions are affected by the increased load on ocean floors; continents should therefore be uplifted slightly relative to the ocean floor. Thus Clark et al. explain raised Holocene shorelines in the Indonesian region as the effect of hydro-isostasy of continental margins in this part of the globe due to deformation of ocean basins after 5,000 a BP when meltwater ceased to enter the basins. Nevertheless, it is unlikely that Holocene sea levels have reached the level of beach rock deposits. Based on this rationale, the shoreline deposits are stratigraphically placed after the collapse and folding of the old Slamet volcano, but before the tectonic uplift prior to the building-up of younger cones.

Notwithstanding the vulnerability to erosion of these shoreline remnants more of the deposits can be expected. The fossil shoreline deposits are positioned on shore platforms of still recognizable shape in the northward facing slope profiles. South of the village Dukuhrandu (see Fig. 4.1) the streambed of the river draining the Tertiary hilly areas contains many fragments of the same beach rock with mollusca shells, indicating the presence of the same marine terraces in this area. A survey in the hills north of the lake Cacaban (see Fig. 4.1), consisting of marine clays of the Middle Pliocene Kalibiuk Formation, indicated similar beach rock fragments at the boundary lowlands with the hilly hinterland.

In the Tertiary hills in kabupaten Brebes, adjacent to the coastal lowlands, similar relict shore platforms are found at altitudes of about 30 to 50 m; for example the northern foot of Gunung Tukung. Although similar shoreline deposits as in kabupaten Tegal could not be located, the extremely smooth and well rounded beach gravels are present as colluvial materials on the surmised relict shore platforms. Further west the geological boundary of the Gintung Formation

---

2 Notwithstanding an expected smooth eustatic sea level rise since deglaciation, emerged Holocene beach deposits and marine erosion terraces are widely encountered along Java's coasts. The present author found many raised beaches, marine notches and remnants of shore platforms both on the north and south coast of Java, situated roughly 2 to 4 m. above present sea level. Tjia and co-workers published many results of interpreted Holocene shorelines on the Sunda Shelf. In a recent paper (Tjia et al., 1983), it is suggested that Holocene sea levels reached maxima of about 5 m above present level, 4,500 a BP. Geyh and Kudrass (1979) give a reconstruction of a sea level curve for the past 7,900 years, based on raised beaches in the Malacca Strait, showing a maximum level of 5 m above present level at 4,500 a ago. Thommeret & Thommeret (1978) mention maximum levels of 1.3 to 2.5 m above present sea level based on raised beaches situated on the toes of Muria volcano, Central Java. Based on morphological studies of raised shorelines in Sulawesi, De Klerk (1983) reconstructs a Holocene sea level curve with a maximum of 5 m above present level at 4,500 a BP.

with the piedmont plain, near the town Sindanglaut, is conspicuously straight. Remnants of a planation level at 20 to 50 m are abundant. Oral information from Hehuwat (1984, LIPI, Indonesian Institute for Sciences, Bandung) stressed the presence of Pleistocene marine terraces on the Gintung Formation in this part of kabupaten Tegal. Unfortunately surveys in this area could not verify the presence of the fossil shoreline deposits.

Near the village Sumber at about 10 km east of the Kromong complex a quarry is present in Late Pleistocene volcanic lahar flows at an altitude of about 60 m. Series of lahar flows are exposed with gigantic flute casts pointing to deposition in a subaqeous environment. In most of the lahar flows the larger boulders seem to have sunk to the bottom of the volcanic mudflow upon entering the aqueous environment, as a result of a sudden loss of consistency of the lahar's mud matrix. The dip of about 20 degrees of the lahar series is directed to the east, suggesting a relation with the uplift of the Kromong complex. This lahar series may have formed part of a volcanic fan in which the distal parts may have been submarine.

In the village Klayan, 4 km north of the town of Cirebon along the road Cirebon-Indramayu, an isolated 150 m diameter steep sloped hill is present surrounded by Holocene coastal lowland deposits. Geologically, it consists of reddish weathered volcanic breccia and conglomerates, horizontally bedded, from the Gintung Formation. The hill is not mentioned on the geological map (Cirebon sheet) by Silitonga & Memed Masria (1978). The top of the hill is remarkably flat and situated at an estimated altitude of 15 to 20 m. If this synopsis of this table hill underlain by the Gintung Formation is correct then the top level must have been connected to the marine terraces near Sindanglaut and SW of Cirebon.

Another geological formation of Pleistocene-Holocene age worth mentioning is the volcanic fan of Balapulang in kabupaten Tegal. Fig. 4.1 shows part of the volcanic fan west of lake Cacaban. The apex of this symmetrically shaped fan is situated about 25 km south of the municipality Tegal. The lithological appearance of the fan materials is fairly consistent and similar deposits, although not having such a spectacular fan shape, are found south of the town Pemalang and in the southern part of kabupaten Indramayu. Many streams radially draining the Balapulang fan in Tegal are incised into the fan thus exposing the fan sediments.

In the lower fan segments mainly dm-bedded fine to coarse tuffaceous sandstones are exposed. The colour varies from reddish-brown to light grey for these fluvially reworked tuffaceous sandstones. The sandstones are well cemented and usually well layered. Fine laminations within a layer point to sedimentation in a fluid environment. Airborne fine tuffs and ash are rare. Occasionally, cmsized angular to sub-rounded pebbles occur. The top of the layers is usually covered by a cm-thick crusts of iron-oxides or horizons in which grains are stained or impregnated by iron-oxides. Groundwater seepage zones yielding iron-rich waters, are found at contacts with these lateritic crust. The tuff grains are angular to subrounded. Bedding orientation is sub-horizontal and the small dip follows the general shape of the fan. Layers can be followed for tens of metres along a river section without much change in thickness. The general lithology and sedimentary structures suggest airborne coarse ash and lapilli which have been reworked by water action in the form of mudflows, sheet floods and ephemeral shallow streams. Remarkable is the apparent absence of carbonaceous matter between the layers.

The significance aspect of this volcanic fan deposit is the fairly consistent lithological appearance; the fan stretches much further to the north than suggested by the geological map of Djuri (1975). In the river Kali Pemali near the road- and railroad bridge near the village Poncol, the volcanic fan deposits are still exposed in the bed of the river about 10 m below the Holocene piedmont plain. South of the town Pemalang similar deposits are exposed, though the reddish-brown colour is much less pronounced and is in many outcrops grey to black. Whereas the sediments in the northern part of the deposit show increasing fluvial structures and become less indurated, towards the south a good similarity exists with the Balapulang fan. Bedding is generally sub-horizontal with tendencies in the northern part for slight southward dips. Both described deposits are derived from the younger Slamet volcano and are positioned stratigraphically at the end of the Pleistocene.

The young volcanoes north of the Bandung basin have produced similar deposits of fairly well-indurated layered tuffs and tuffaceous sandstones with sub-horizontal bedding. The tributaries of the river Cimanuk in the southern part of kabupaten Indramayu, near the boundary between the piedmont plain and the Late Pliocene Citalang Formation, have incised similar indurated tuffs. In particular the rivers Ci Panasaat and Ci Panas near Cikawung offer good exposures of these tuff layers beneath a Holocene cover. Koolhoven (1934) reports horizontally bedded indurated Prahu tuffs in the area of kabupaten Subang, which resemble the Balapulang tuffs in both lithology and extension, and he assumes a young Quaternary age.

4.2.4 General patterns of Pleistocene tectonics

Patterns of geological deformation vary widely within the provinces of West- and Central Java. The variations are caused by differences in intensities and types of deformation. The major deformations seen today originated during the Late Pliocene and the Quaternary. Distinct periods with geological deformation are hard to recognize within the volcanic arc and the back-arc region. The impression is gained of a more or less continuous deformation as early as the sedimentation phase upon which more intense deformations are superimposed either locally or regionally. Breaks in the stratigraphic record clearly expressed by angular unconformities in a particular area are apparently absent in neighbouring areas. Evident stratigraphic breaks may differ widely in geochronological time between regions.

Despite the complexity of the geological structure, some regularities can be noticed. Fold system trends of regional extent show gentle to open folding in the southern part of West- and Central Java with increasing deformation to the north in asymmetrical tight folds, incidentally overturned, with sets of northward directed low-angle thrusts in the most deformed zones. These zones are found north of the island's longitudinal axis. Beyond this strongly deformed zone, although this may also differ from one area to another, the complex structure changes rapidly to almost undeformed horizontal layers with gentle dome and basin structures. Sutarso & Patmosukismo (1978) notice that all tectonic structures offshore discovered so far are much gentler than those onshore. These relatively undeformed sediments have already been found under the present-day coastal lowlands in kabupaten Indramayu (Soetomo & Sujanto, 1978 and Padmosukismo & Yahya, 1974) and extend northwards beneath the Java Sea. Hamilton (1979) mentions broad folds and low-angle unconformities in sediments on the continental shelf of the Java Sea.

Fig. 4.3 summarizes the major structural features of West- and Central Java. Several striking differences in structure can be noticed between West-, Central- and East Java:

1) the abrupt changes in coastline and total island width approximately coinciding with the administrative boundary between West- and Central Java. The coastline changes are repeated between Central- and East Java. The coastal lowlands in West Java are much broader with impressive deltas. Within West Java coastline changes are found also near Jakarta and the Pelabuhanratu bay;
2) the magmatic arc in West Java consists for the larger part of a double row of volcanoes separated by intramontane basins. Intramontane basins are absent in Central Java and only a single row of volcanoes is present. The same pattern is also found in East Java with a single row of volcanoes spaced much more widely than in West- and Central Java;
3) Pannekoek (1949) describes the conspicuous geomorphological differences between the Central Zones of West Java on the one hand and those in East- and Central Java on the other. According to his description, 'the volcanoes in West Java are not situated on a straight line in the middle of the depression but form irregular groups which are more or less separated by depressions'. He notices further that the western part of West Java (zone I) should be excepted from the description of the Central Zones as it 'does not conform to it at all';
4) the major trend line, as estimated from available geological maps, of the geanticlinal axis of Java shows signs of not being collinear. The same applies to the magmatic arc having axes which do not appear to be lying end to end on a straight line;
5) the Southern Mountain zone consists of practically undeformed tilted plateaus with southward directed dip slopes of vast extent and is found only in West- and East Java. Pannekoek (1949) remarks that the Southern Mountain Zone in West Java 'ends abruptly' in the Pelabuhan Ratu Bay where it is succeeded by a deep sea basin;
6) the anomalous locations of the volcanoes Gede in the northwest corner of West Java and perhaps the Ciremai and the Muria in Central Java far from the main volcanic line, have geochemical compositions of extruded rocks which are different from the rows in the south. This rare composition of potassic volcanic rocks as erupted by Muria volcano is only known in isolated spots (according to a map of Katili, 1975) on Bawean island north of the Madura strait, In East Java along the Java-Bali strait and near the town of Bima on Sumbawa island. The N-S trending row of volcanoes comprising Ungaran, Soropati, Merbabu and Merapi is also somewhat anomalous;
7) West Java features a long thrusting zone north of the magmatic arc which can be traced from kabupaten Cirebon almost as far as Bogor. Towards Central Java the thrusting zone terminates after a dextral deflection;
8) as argued above, important volcanic activity in Central Java and West Java in zone I began as early as the Lower Pleistocene. West Java is characterized by regional thrust movements at the end of the Pliocene which continued locally until the Lower Pleistocene, giving rise to a regional unconformity at the Plio-Pleistocene boundary. Major volcanic activity in West Java originates from the Middle Pleistocene. However, an exception must be made for the presumably Lower Pleistocene volcano of the Kromong complex, north of the present Ciremai cone in kabupaten Cirebon. Nevertheless, it appears that regional volcanism in the Lower Pleistocene was mainly confined to the zones I and III;
9) the conspicuous difference in tectonic styles between West-, Central- and East Java. Structures found in the Rembang hills and the Kendeng ridge consisting of regional simple fold systems with steeply dipping axial surfaces are completely lacking in Cen-

tral- and West Java, in which asymmetrical shallow folds and thrust belts predominate[3]. Van Bemmelen (1949, p:571) mentions contrasts in the sedimentary columns for areas in the Kendeng anticlinorium west and east of the Solo-Gundih railroad. He further notices that a strip of negative isostatic anomalies in the Kendeng zone ends to the south of Semarang (p:577).

Three types of folding can be recognized, viz. two regional systems and a local system around volcanic cones:

1) a sub-regional E-W trending system with simple fold structures and steep axial surfaces driven by diapiric uplift of Miocene and Pliocene marine mudstones, in which deformation is a continuous process after being initiated in Late Pliocene times;
2) a regional E-W trending system of open to tight folds with respectively steep to gently dipping axial surfaces, locally even overturned, cut by upthrust faults and in the deeper parts presumably accompanied by décollement zones resulting from gravitational outward gliding against the geanticline;
3) a local highly complex folding pattern around major volcanic cones with radial strike-slip faults, asymmetric folds and low-angle thrust faults all originating from gliding movements after volcano collapse. Another type of deformation found only on the foot slopes of volcanoes are the diapiric structures caused by the upbulging of incompetent Upper Tertiary rocks from beneath the volcano body towards the toes[4]. Striking examples are the dome structures of Sangiran etc. around the Lawu volcano and other volcanoes in Central- and West Java.

The sub-regional folding with E-W trending axes was mainly formed, or at least initiated, during the Late Pliocene. The folding structures caused by rising shale and clay diapirs are active up to the present-day in East Java.

3 The antiforms in the Rembang hills are closely folded and relatively narrow forming pronounced regional ridges, as compared to the broad and openly folded synforms. The antiforms are accompanied by graben structures in the crests. Oil seeps are common in the antiform structures. The driving mechanisms behind these structures, which were already active in Late Pliocene and Early Pleistocene times as evidenced by the dark red lateritic paleosols near the hinges, appear to be clay and shale diapirism. However, in the broad and open synforms of the Randublatang zone clay diapirism also appears to be active and is forming anticlinal structures by rising clay plugs and ridges, as evidenced by the mud volcanoes of Kuwu Bledug and the warm salt water springs at Jono. Nevertheless, one may expect broad valleys such as the Randublatang zone and the Demak-Kudus-Pati valley to be subsiding zones as the diapirs are driven towards the narrow anticlinal ridges. Perhaps the sloping planation surfaces on Pleistocene deposits found in the Randublatang zone may hint at subsidence movements. A regional normal fault is present on the northern flank of the Grobongan-Sukolilo anticlinal, N of the town Purwodadi, with marine abrasion niches at a present altitude of about 30 to 60 m.

4 Striking examples have been found by the present author around the Lawu volcano (Sangiran dome and related structures), Muria and Ciremai volcano complexes. The Sangiran, Gemolong and Gesi domes are not caused by compressive forces as suggested by Van Bemmelen (1949) but by diapiric upbulging of Miocene and Pliocene rocks. Inliers of Upper Tertiary rocks piercing the toes of Quaternary volcanoes are found along many volcanoes (Ciremai, Tangkuban Perahu, Muria, Salak, Gede etc.)

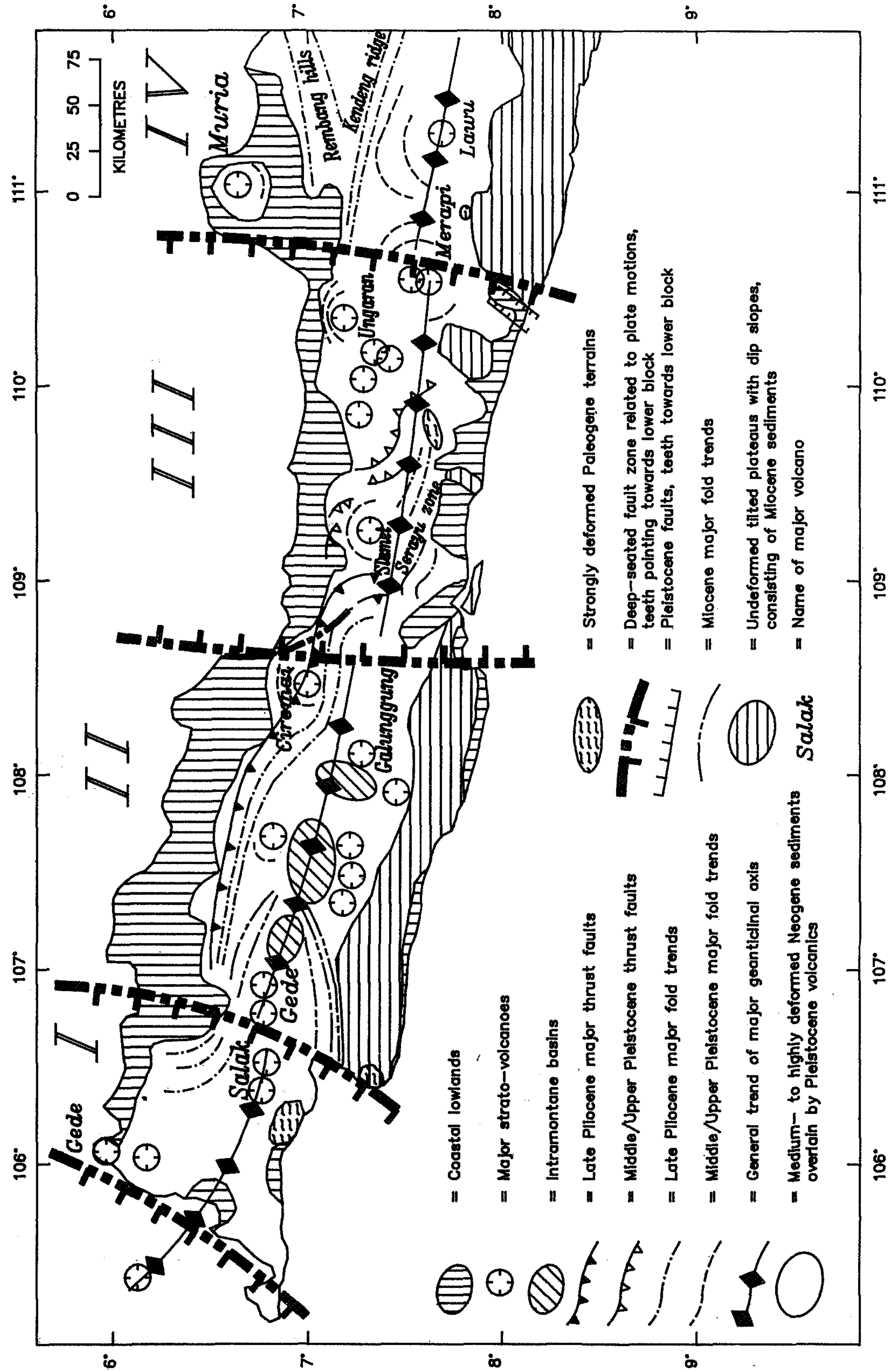


Fig. 4.3 Major structural features and surmised structural zoning in West- and Central Java.

The Upper Pliocene Kaliglagah and Upper Damar Formation in Central Java, with abrupt facies changes from fluviatile to marine environments, indicates syn-orogenic uplifts which coincide with the main deformation. Local or regional scale uplift gives rise to gravitational gliding reactions of the sedimentary epiderm.

Folding in West Java may have started more or less synchronously by uplifting movements. The uplifts must have been more intensive and of a regional character especially towards the end of the Pliocene to give the long thrusting zone. A peculiar feature of the thrusting zone is its abrupt termination in the western part of Central Java with a clockwise curving of the thrust faults. The thrusting zone is apparently not covered by the old and younger volcanic cones, but obviously curves towards the south. The impression is gained of substantially higher uplift intensity in West Java which led to gravitational gliding towards the lower blocks.

The Pliocene and Plio-Pleistocene structures are deformed by collapses of the huge cones of the old volcanics from the Middle Pleistocene. The folding and radial outward thrusting structures around volcanic cones is well expressed in Central Java. In particular the collapse of the Old Slamet volcano caused well developed examples of foot folding and outward gliding. The volcanoes of the Dieng plateau in the middle of Central Java, have also triggered well pronounced gliding reactions in south and southwesterly directions.

A remarkable coincidence can be noticed between the major structural features described above and the shape and flexures in the coastline of the island. Abrupt flexures in the coastline on the north side appear to correspond with flexures in the south. Based on coastline shape and the structural characteristics enumerated above, the entire island of Java can be subdivided into more or less equally sized structural compartments; Fig. 4.3 shows this zoning for West- and Central Java only. A similar zoning can be found in East Java. Thus a fourth zone runs as far as a N-S line across Surabaya[5] and a fifth extends towards the sea strait between Bali and Java.

This structural zoning is thought to be related to differences in plate movements beneath Java during the Pleistocene. Small differences in dip of the underthrust plate between the structural sections influence the intensity and lateral position of magma generation. The structural sections must be bounded by deep-seated transverse zones of crustal weakness.

The following arguments can be advanced to favour subdivision into coherent structural sections bounded by deep-seated transverse faults:

1) a glance at the map shown in Fig. 3.2 shows continuation of the surmised faults into the basin and arch structure under the Java Sea. In particular the Seribu platform situated just north of zone I appears to be bounded by transverse fault structures. The fairly straight western boundary of the Karimunjawa arch is conspicuous and suggests structural control. The sedimentary basins on the northern side of the West Java Basin, the Cirebon trough and the East Java basin all appear to fit into this surmised structural compartment configuration;
2) the discontinuity of the magmatic arc across the N-S trending fault structures, particularly between structural zones I-II and II-III;

---

5 Pannekoek 1949) mentions the numerous transverse faults between the Rembang zone and the continuation of the anticlinorium in Madura, and concludes that the narrow Madura Strait is determined by transverse faults.

3) the position of the volcanoes Muria, Lasem (near Rembang), Gede (northwest corner of West Java) and presumably also the Ciremai, far from the main magmatic arc but near these transverse fault zones. The geochemical composition of the Muria volcano (potassic volcanics) is unmatched by volcanoes in the central magmatic arc which consist of calc-alkaline volcanics. Similar highly alkaline basalts as found in the Muria complex are also present in the Karimunjawa arch. Katili (1975) notices the peculiar position of these 'plateau basalts' found also in Lampung (Sumatra) and remarks that they are probably not related to the Benioff zone. Potassic volcanic rocks exposed in the Muria volcano complex, in the northeast corner of East Java along the sea strait with Bali and on Bawean, all suggest relations with the conjectured N-S transverse faults. Kienle et al. (1983) pointed out that distinct geochemical types of magmatism exists near subsegment boundaries as compared to volcanoes within arc segments;
4) fold systems and structural regions generally terminate in the vicinity of deep-seated fault zones. The tight anticlines in East Java near Rembang and Blora and the Kendeng anticlinorium showing signs of diapiric upward movements in the fold cores, terminate abruptly near the transverse zone between zones III and IV. Important changes in tectonic style are found along the deep-seated fault zone between zones I and II. In this respect the curvature in fold trends north of the Salak volcano is spectacular;
5) the abnormal N-S trending strike of the Late Pliocene folds in Cirebon-Brebes and Tanggerang regions close to the deep-seated boundary faults of structural section II. Van Bemmelen (1949, p:633) mentions the anomalous strike of the folds in Tanggerang. In addition, the same author noticed that the 'Java geanticline becomes suddenly much broader' east of Pelabuhan Ratu bay;
6) satellite images (Landsat 1974) reveal a clear lineament from the eastern coast of Cirebon (see Fig. 4.3) curving SE towards the kabupaten of Brebes and crossing the Ci Sanggarung river at the village Luruhgung[6];
7) for the northern part of West Java the geological cross sections of Padmosukismo & Yahya (1974) display distinct fault steps in the basement going from zones I to II (from less than 1,000 m depth in zone I to slightly more than 4,000 m in II).
8) as will become apparent later, groundwater basins in the northern coastal lowlands are similarly bounded by N-S trending fault zones. The present configuration of the coastal lowlands, broad in zone II and narrow in zones I and III, fits remarkably well into the proposed structural zoning.

The arguments enumerated above indicate that the shape of Java, the configuration of the Pleistocene-Holocene magmatic arc and the structures under the Java Sea are all controlled by deep-seated N-S trending zones of crustal weakness. The present-day shape and structure of zone II can explained by stronger uplifts during the Pleistocene compared with the uplifts of ascending magmas in zones I and II. Based on the lateral offsets of volcanic lines crossing the transverse zones, it is expected that the dip of the Benioff zone varies

---

6 From Landsat images the point of crossing the Ci Sanggarung river appears to be located near the bridge at the village Luruhgung. Halang marine mudstones alternating with tuff layers are exposed along this lineament crossing. Near the bridge many small offsets and slickensides can be discerned in the well-layered Halang Formation and are thought to be related to the lineament. The micro- and meso-scale faults and dislocations were only found near the bridge.

across the transverse zones. The more intensive uplifts, presumably caused by higher magma production, arched the geanticline after which a collapse took place at the crest along normal faults parallel to the geanticlinal axis. This collapse resulted in the formation of the intramontane basins of Cianjur, Bandung and Garut. After the collapse along normal faults magmas could finally reach the surface and subsequently produced the double row of volcanoes. Stronger uplifts and an expected greater production of volcanic rocks created a large rock mass prone to degradation processes. Hence, a much larger sediment load was available for deposition in the northern coastal lowlands and the Java Sea. The significantly broader belt of coastal lowlands in structural zone II must then be attributed to the availability of high sediment loads from the hinterland.

If a relation is suggested between the N-S trending transverse zones of crustal weakness with the configuration of Neogene basins in the Java Sea and along the northern rim of Java and the elevated basement blocks such as the Karimunjawa arch, it then follows that these transverse faults must have already originated during the Middle Oligocene event of 35 Ma ago. Adopting this rationale, these transverse faults have been developed in the quasi-continental crust of coalesced tectonic melange wedges and reach as far as or even into the peripheral zones of the real continental crust as exposed in the Karimunjawa islands. Once the zones of crustal weakness were created, presumably during the 35 Ma event, they persisted as active movement zones up to the present.

4.2.5 Tectonics in the hinterlands south of the northern coastal lowlands

The previous chapter stressed the intricate patterns of tectonic structures in the Neogene sediments bordering the horizontally layered fluvial and marine sediments of the northern coastal lowlands. Regional fold systems with steeply or gently dipping axial surfaces, often accompanied by thrust faults, are well expressed as topographical ridges and plateaus which seem to vanish abruptly underneath the alluvial cover of the coastal lowlands. The boundary between these two tectonic and sedimentary units is generally rather straight or smoothly curved without any irregularities. Outliers of Neogene rocks piercing through the alluvial cover are absent in the coastal lowlands except for the Lower Pliocene Prupuk reef in the vicinity of the river Kali Pemali, south of the town Brebes and the N-S trending anticlinal structure around the Kromong complex in Cirebon. The abrupt change in terrain slope going from the coastal lowlands to the deformed Neogene sediments and thus from a depositional landform to a strongly erosional one, is uncommonly sharp. Aerial photographs render the same impression. Only along short stretches in the kabupatens Cirebon, near Palimanan and in Brebes near the river Kali Pemali is a more or less smooth transition from lowlands to hinterland manifested. In all the remaining studied kabupatens, notably in Tegal, Brebes, Indramayu and Subang, the changes in terrain slope at the boundary between lowlands and hinterland are uncommonly sharp. In these locations the alluvial deposits of the lowlands appear to abut against an escarpment-like topographical ridge or plateau. This escarpment-like geomorphology suggests a kind of structural control. Even in hypothetical settings with raised base levels of erosion and drowned valleys one may expect erosional remnants of Neogene sediments piercing through the younger horizontally-layered fluvial deposits, or at least a capricious line of intersection between the erosional topography and the abutting younger fluvial deposits.

Returning to the coastal lowlands, the tectonic structure of the Upper Tertiary rocks of the hinterland dipping under the Quaternary coastal lowland deposits is of paramount importance to groundwater flow. In some areas, tube wells may penetrate tens of metres into the Quaternary sediments near the boundary with the hinterland, which suggests a rapid deepening. Since the southern belts of the coastal lowlands are the recharge areas, the structural configuration in the underlying Upper Tertiary basement is expected to affect streamlines of groundwater flow. Being completely hidden from sight and in the absence of any reliable lithological borehole logs down to basement in the southern belts, this remains a difficult puzzle to unravel.

The following facts are thought to be important for disentangling the structures under the coastal lowland sediments:

1) according to the cross sections through north West Java by Padmosukismo and Yahya (1974), the Miocene and Pliocene series beneath the coastal lowlands constitute a pile of argillaceous sediments intercalated by extensive carbonate horizons and reaching a total average thickness of about 3,000 m. The tectonic structures of very gentle open fold systems with broad dome structures and depressions are cut by local to regional syn-sedimentary faults, in strong contrast to the tectonic styles of tight asymmetric folds with thrust faults as found along the southern border of the coastal lowlands. The structural association resembles a gentle dome and basin structure with local faults parallel to hinge regions; perfectly illustrated by the cross section of Soetomo and Sujanto (1978) through the Kandanghauer structure in the northern part of kabupaten Indramayu. Conspicuous is the fact that an Upper Miocene limestone horizon (Parigi carbonates, suggested in previous sections to be the stratigraphic equivalent of the limestone lenses in the upper part of the Halang Formation) is found at a depth of more than 1,000 m, and that Lower Miocene rocks are situated at depths ranging from 2,000 to 3,000 m. This depth configuration appears to extend far to the south, for instance to the Pasir Putih basin near the town of Cikampek in kabupaten Karawang, whilst at a distance of 5 to 10 km further the Miocene and Pliocene rocks are widely exposed;
2) many exposures of the Upper Miocene Halang Formation can be found on the foot slopes of the volcano Slamet, south of kabupaten Tegal. The average altitude of these exposures is about 1,000 m above M.S.L., with a maximum of 1260 m. On the western foot slope of the volcano Ciremai, Oligocene shales and calcareous sandstones outcrop at altitudes of up to 1,000 m above M.S.L. Further to the west the same rocks are exposed as a tightly folded structure at altitudes of about 500 m;
3) near the village Waleddesa along the river Cisanggarung on the administrative border between Cirebon and Brebes a successful deep water well has been drilled (under the supervision of the water supply consultants IWACO) at a distance of about 500 m north of the outcropping Upper Pliocene Cijulang Formation. Judging from the lithological borehole logs the 150 m deep well withdraws water from the Gintung Formation;
4) in exposures of Neogene rocks along the southern border of the coastal lowlands faults including fresh slickensides are always present at outcrop scale. The general tendency of tectonic movements appears to be northward directed thrusts with backward rotation of the bedding to slightly southward dipping orientations;

5) spectacular escarpments related to fault tectonics are found near the town of Weleri about 40 km west of the town Semarang, also indicated by Pannekoek (1949) on his geomorphological map of Java. Along the mainroad from Semarang to Weleri, especially near the village Kaliwungu, the Upper Damar Formation (Lower Pleistocene lahars and redeposited volcanics) clearly constitutes a cliff with marine abrasion features (niches etc.); due to higher sea levels during the Holocene (4 to 6 m about 4,500 years ago). In the river Kali Kuto, north of Weleri, the present author found Holocene bluish marine clays in the river bed which clearly underlie the fluvial cover. These marine clays fit well into the picture of a Holocene sea abrading the Upper Damar hills. Van Bemmelen (1941) assigns the name Tjandi hills to the area south of Kaliwungu and concludes that the cliff concurs with flexure- or fault escarpment. Based on the numerous deep water wells in the area around Semarang, which seem to reach the Upper Damar deposits at a depth of about 100 m, he estimates that the total throw of the fault amounts to 100-150 m. He notices further that immediately in front of the Tjandi hills the coastal lowland deposits have already attained a considerable thickness. Van Bemmelen finally advances the hypothesis that the E-W marginal flexure probably has a regional significance.
   The marginal flexure can followed much further to the west to the northern face of the Upper Damar hills, reaching the sea between Weleri and Batang. Especially southwest of Weleri, the present author is inclined to the opinion that the geomorphology strongly suggests the presence of more E-W flexures all bounded by steep escarpments. In this area at least three escarpments can be recognized, each bordering plateaus;
6) the present position of the Late Pleistocene beach rocks (40 to 50 m above M.S.L.) found on northern flanks of the hinterland hills in kabupaten Tegal is incompatible with maximum eustatic sea levels during the last interglacial; thought not have exceeded present-day sea levels (Batchelor, 1979; Chorley et al., 1984). The same applies to exposures at the same altitude at the foot of the Ciremai volcano in kabupaten Cirebon. To complete this picture, many sites along the first row of hills in the hinterland suggest marine abrasion terraces and cliff-like morphologies, such as:

   1) the surmised marine terraces on the foot slopes of the Ciremai volcano;
   2) the marine abrasion shoulders in the hills near the villages Gongseng, Sigentong, Waled, Banjarharja and presumably near Tomo;
   3) the steep northward facing cliffs in the Kumbang Formation near the hamlet Nambo (Banjarharja) and Karangbale suggest marine abrasion similar to the abrasion features found near Weleri;

   Since these mentioned sites and locations are situated well above the present-day sea level, it must be concluded that tectonic movements have taken place in the Late Pleistocene.

The above facts strongly suggest structural control of the intricate boundary between the hinterland and coastal lowlands. Six geological cross sections have been constructed at various locations along the hinterland boundary to illustrate the surmised tectonic structures underneath. All have been chosen in areas surveyed by the present author and therefore some sections deviate from the geology indicated on the 1:50,000 geological sheets.

The cross sections are depicted in Fig. 4.5a to 4.5f and the locations are indicated on Fig. 4.4.

The sections of Fig. 4.5a to 4.5e all show intricate upthrust structures with some grading into to real overthrusts. Clear transitions exist between dominant folding to dominant thrusting. The orientation of bedding in the various formations just south of the Quaternary lowland deposits is based on field measurements carried out by the present author. Generally steep bedding dips which vary from 30 to 80 degrees are found in the Pliocene formations in the hinterland hills adjacent to the lowlands. The steep bedding orientation originates from upthrust movements in which even tectonic wedges are formed.

The main tectonic movements at a regional scale during the Pleistocene epoch consisted of a geanticlinal uprise in the south compensated by deep normal faulting in this major hinge zone, trending along the southern border of the coastal lowlands. These primary tectonic movements were then followed by gravitational outward gliding of the sedimentary epiderm in the south. It is likely that major décollement zones are present along which repeatedly gliding movements have occurred. The effect of these secondary gravitational glides is the bending over of the original deep normal fault planes. These toppled-over normal faults appear to have been deformed further into upthrust and low-angle overthrust faults with tectonic wedges squeezed towards the north.

The structures of Fig. 4.5a to 4.5d are more complex than those in the sections of Gongseng and Weleri (Fig. 4.5e to 4.5f). The latter in particular still shows normal faulting as the major tectonic component. It accords with the major tectonic elements shown in Fig. 4.3, in that the gliding movements in West Java up to the Bumiayu area (Central Java) are more pronounced than further to the east.

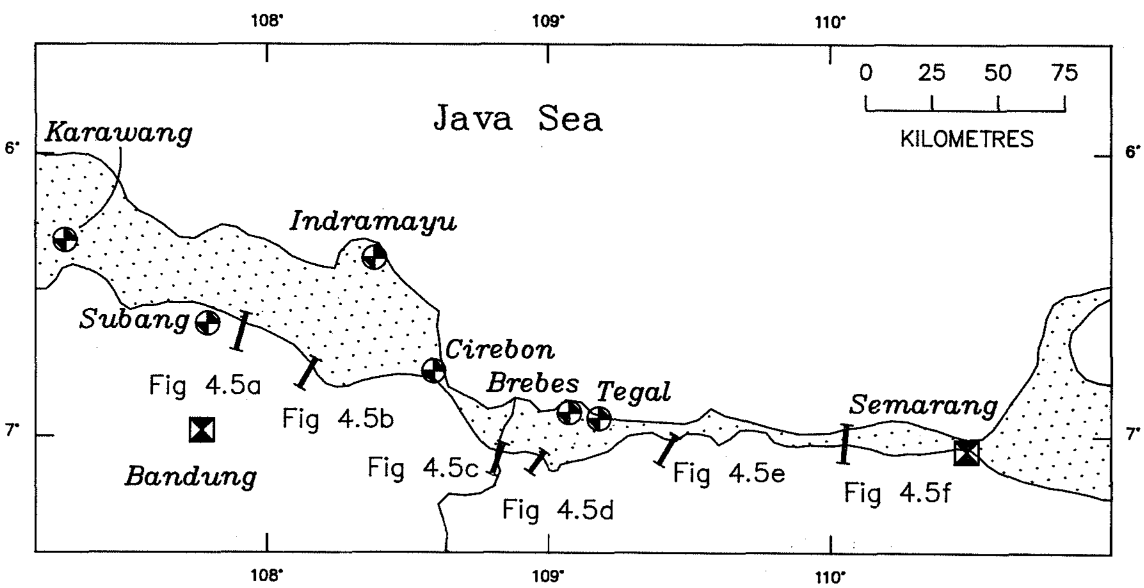
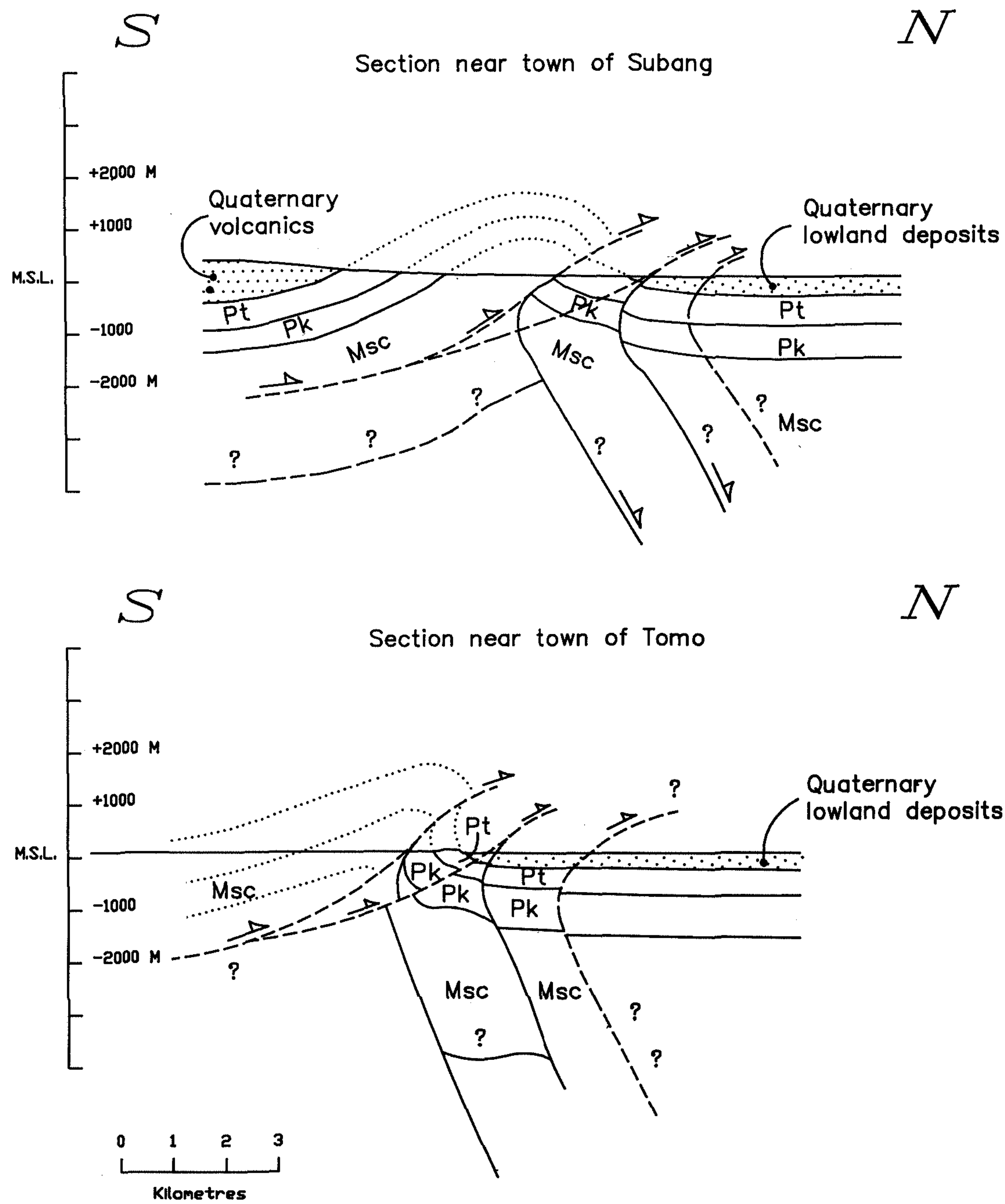


Fig. 4.4 Location map of the geological cross sections shown in Fig. 4.5a to 4.5f.

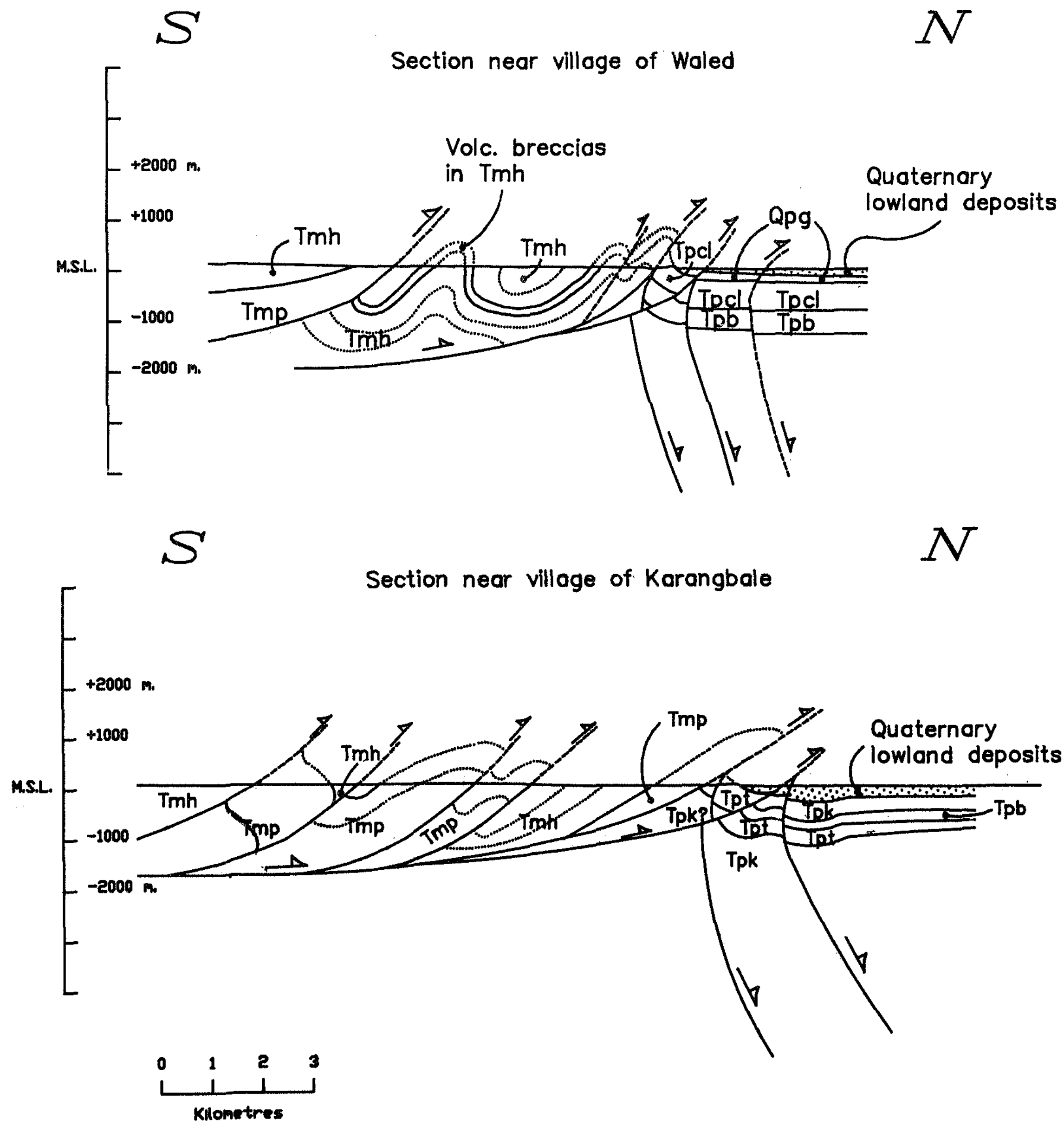


Pt = Citalang Beds; marly tuff–sandstones and polymict conglomerates (Upper Pliocene ?)

Pk = Kaliwangu Beds; dark marine clays, shales (Middle Pliocene)

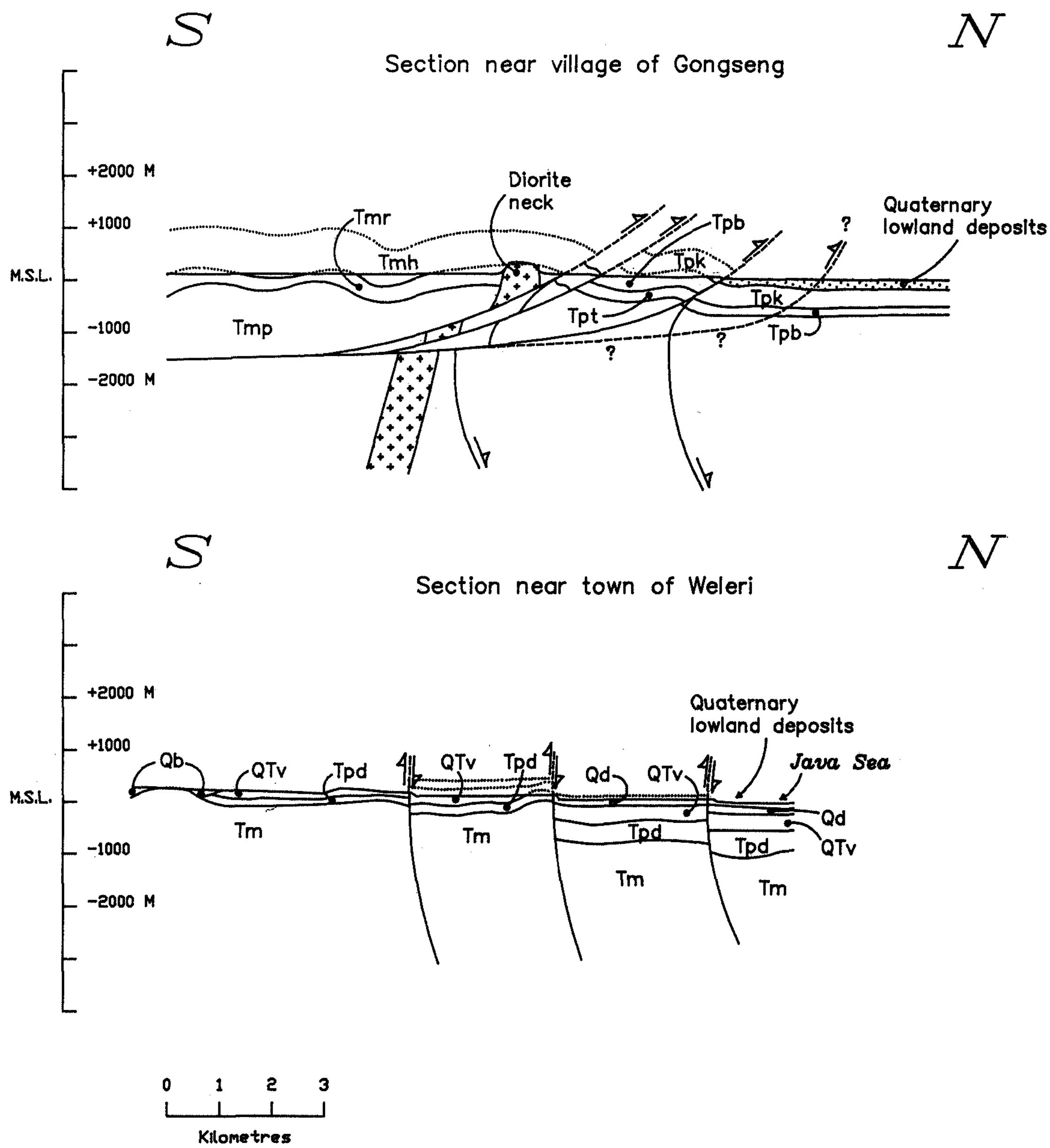
Msc = Subang Beds; mainly shales with tuff– and minor limestone layers (Upper Miocene – Lower Pliocene)

Fig. 4.5ab Cross sections near the towns of Subang and Tomo in West Java.



Tpcl	= Cijulang Beds; marly tuff–sandstones, shales (Upper Pliocene)
Tpb	= Kalibiuk Beds; marine clays, claystones, marls (Middle Pliocene)
Tpt	= Tapak Beds; light–coloured crystal tuffs with reef limestones in the top (Lower to Middle Pliocene)
Tpk	= Kumbang Beds; andesitic volcanic breccias (Lower Pliocene)
Tmh	= Halang Beds; marine claystones, shales and tuff–sandstones (Upper Miocene)
Tmp	= Pemali Beds; Globigerina marls, claystones (Lower Miocene)

Fig. 4.5cd Cross sections near the villages of Waled and Karangbale in Central Java.



Qb = Notopuro Beds; volcanic breccias, lahars (Middle to Upper Pleistocene)

Qd = Upper Damar Beds; claystones, tuffs, conglomerates, lahars (Lower Pleistocene)

QTv = Middle Damar Beds; volcanic breccias, tuff–sandstones, conglomerates (Lower Pleistocene)

Tpd = Lower Damar Beds; coastal lowland muds, polymict conglomerates, tuffaceous sandstones (Upper Pliocene)

Tpk = Kaliglagah Beds; equivalent to Lower Damar Beds

Tm = Undifferentiated marine beds, claystones, marls, shales, minor limestone beds (Miocene, Pliocene)

Fig. 4.5ef Cross sections near the village of Gongseng and town of Weleri in Central Java.

Complicated structures with imbricated faults, squeezed out tectonic wedges and dipping fold planes are found in the sections of Waled and Karangbale (see Fig. 4.5c and 4.5d). In spite of the radial outward gliding with many transverse faults in the foot slopes of Slamet volcano (Central Java), the fold structures shown in Fig. 4.5e are much less complex than those shown in figures 4.5a to 4.5d. Thrust structures in the section near the village Gongseng (Fig. 4.5e) are confined to a narrower belt than those depicted in Fig. 4.5c and 4.5d. Much less deformed are the structures near Weleri (see Fig. 4.5f).

As mentioned previously, many features can be recognized at the scale of a single outcrop such as minor faults with slickensides and fresh striae, drag folds, pressure wedges, small offsets along sets of minor faults and backward-rotation of alluvial deposits, all indicating the presence of young to recent tectonic movements. An impressively large slab of rocks measuring several square kilometres has glided backwards to the south near the town of Majalengka, as a further reaction to the northward directed gliding movements near the town of Tomo. The impression is gained, supported by local inhabitants' reports of frequent earth tremors, that the tectonic movements are still active as expected in these gravity driven systems. Conspicuous is the sharp transition from the thrust belt to the relatively undeformed Tertiary sediments of gentle basin and dome structures under the coastal lowlands. However, low-angle thrust faults can be expected underneath the southern rim of the coastal lowlands, implying that a cascade-like morphology is likely in the top of the Tertiary sediments.

Since the movements are thought to be still active and started with varying intensities at the end of the Pliocene with peak activities during the Middle Pleistocene, it follows that the Quaternary sediment pile beneath the coastal lowlands must have also been affected. However, the zone of influence towards the north remains obscure. According to the cross sections the zone of influence can be expected to have a width of only a few kilometres. The sequence of tectonic movements is difficult to trace because of gravitational reactions to uplift. At least three major uplift events can be expected, viz. at the end of the Pliocene, roughly in the Middle Pleistocene and most likely also at the boundary Pleistocene-Holocene.

Concerning tectonic structures along the southern border of the coastal lowlands the following conclusions can be drawn:

1) the southern fringe of the coastal lowlands coincides tectonically with the major hinge zone between the geanticline in the south and the sedimentary basins in the north;
2) the complexity of structures increases dramatically near the hinge zone and culminates in imbricated upthrusts and overthrusts. On the other side of the hinge zone the structures are simple, consisting of basin and dome structures with gentle folding which is apparently not influenced by the thrust movements;
3) the geanticlinal uplifts during the Pleistocene reached hundreds of metres and are most likely to have been accompanied by deep normal faulting in the hinge zone. Secondary reactions to the geanticlinal uplifting are gravitational gliding of the sedimentary epiderm, promoted by the highly incompetent clay and shale lithologies along major zones of décollement;
4) deformation near the hinge zone in West Java to Bumiayu (kabupaten Brebes) bears a more regional character and has progressed further than that for the same zone in Central Java where the structures are mainly draped around the major volcanoes;

5) it is expected that the low-angle thrust faults are also present under the southern periphery of the coastal lowlands. The most likely structures, affecting both the Tertiary and Pleistocene sediments, are gentle folding with dipping axial planes and imbricated thrust structures giving rise to a cascade-like morphology of the Tertiary basement;
6) the considerable thickness of Quaternary lowland deposits near the southern border is related to these imbricated thrust structures;
7) the coastal lowland deposits abut a major tectonic thrust belt, which connects the shallow fold systems in the south with the deeper dome and basin structure beneath the lowlands;
8) the conspicuous and abrupt change in topography and land slope along the border between the hinterland and the northern coastal lowlands in West- and Central Java is structurally controlled.

4.2.6 *Summary of the major geologic events during the Pleistocene*

Combining the structural zoning for Java proposed in a previous chapter with the global geological history of Pleistocene volcanism, a summary can be compiled of the major geological events during the Pleistocene. The last column of Table 4.1 lists the inferred major events during this period.

Uplift started in the Late Pliocene in Central Java creating unconformities which become more pronounced in a southern direction. The boundary Pliocene-Pleistocene appears to have been relatively quiet in Central Java as compared to West Java. The major thrust structures at the southern border of the northern coastal lowlands were formed at that time. The onset of the Pleistocene is characterized by sub-regional uplifts created by ascending magma bodies. Lower Pleistocene volcanism is known mainly from Central Java. Towards the Middle Pleistocene the ascending magmas and corresponding uplifts must have gradually attained a more regional character.

The N-S trending deep-seated faults most probably became active during this stage of ascending magma at a plate sector/segment scale, thus involving the entire island of Java. The geological age of the faults probably extends into the Tertiary, being most likely related to the 35 Ma event. The remarkable correspondence in trends (see Fig. 1.3) between the N-S faults and the basin and warp structure of the crust under the Java Sea suggests a structural relation. Hamilton (1979) holds the view that the structural relief of the basins north of West- and Central Java predates the deposition. If a structural connection is assumed then it follows that the N-S faults are much older zones of crustal weakness, reactivated during the Pleistocene. Another argumentation in favour of an age of at least Tertiary for the N-S faults is the much thinner sedimentation in zone III as compared to zones I and IV (Hamilton, 1979). The thinner sediment cover is attributed by Hamilton to the basement high between the West Java basin and the East Java-Madura basin. The vertical movements along the N-S faults must have reversed from the Tertiary into the Pleistocene. Thus upfaulting of zone III or downfaulting of zones I and IV during the Tertiary and vice versa during the Pleistocene.

Widespread ascendance of magma bodies during the Middle Pleistocene caused a collapse of the crustal E-W trending warp in West Java which gave rise to formation of the intramontane basins. The magmas finally reached the surface along the collapse faults and the building of the double row of volcanoes started in West Java. In Central and East Java the outpouring of volcanics was concentrated along the centre of the magmatic arc. The Middle Pleistocene must have been a time span with widespread volcanism and nearly all the younger Holocene cones are built upon ruins and collapsed volcanoes dating from the Middle Pleistocene. The loading of huge strato-type volcanic cones on the highly incompetent clayey rocks of Tertiary age provoked foundation problems and collapse, and ring fault structures are repeatedly found in the old volcanics. Upwarping of the incompetent clayey rocks from beneath the old volcano toes in the form of diapiric structures, asymmetric folding and outwardly glided cone sectors are common structural phenomena.

The fossil marine terraces found in Tegal and presumably also in Brebes, Cirebon and Indramayu must have developed after the foot folding of the Pliocene rocks by the old Slamet volcano (see Fig. 4.1). The present altitude of fossil beaches at about 40 to 60 m points to subsequent tectonic uplift. If this reasoning is correct then the fossil marine terraces must have been formed during the last interglacial period of the Pleistocene, thus during the Upper Pleistocene. The uplifts evidenced by these raised marine terraces ushered in the last major volcanic period at the Pleistocene-Holocene boundary. Rising magma bodies must have again resulted in uplifts, before the magmas reached the surface using the existing and mostly clogged vents of old volcanoes. The onset of the last volcanic period must have been fairly violent and explosive. Almost all the larger young volcanic cones are built on the ruins of old Middle Pleistocene volcanoes.

The emergence of Java started to take shape at the end of the Pliocene with deposition of the regressive Kaliglagah, Cijulang and Citalang Formations containing erosion products of older formations from the south. The paleogeography at the transition from Pliocene to Pleistocene may have consisted of vast marshy coastal lowlands with rapidly shifting shorelines featuring limnic and estuarine environments. Local volcanic cones were built up in this environment in the Lower Pleistocene. However, the most important structural molding of the island to render an almost continuous magmatic backbone occurred during the Middle Pleistocene. The uplifts and subsequent outpouring of huge amounts of volcanic material counteracted degradation processes. A further moulding of structural shape was achieved by the Pleistocene-Holocene volcanic period.

4.3 Climatic conditions during the Pleistocene

4.3.1 Introduction

The sediments in the subsoil of the northern coastal lowland belt in Java have been deposited in the Quaternary period, in which global climatic fluctuations occurred with rather high amplitudes and frequencies. Temperature fluctuations between warm and cold episodes may have amounted to more than 15^{0}C in some parts of the world and at least twenty glacial-interglacial cycles may have occurred throughout the entire Quaternary (Lowe & Walker, 1984). These paleo-climatic oscillations have important repercussions on pedogenetic and morphological processes, not merely in the temperate climatic regions but also as recognized in the late 1950s by scholars such as Cailleux, Tricart and Fairbridge, in the low-latitude tropical areas. Prior to the late 1950s many workers believed that tropical humidity was accentuated during glacial times, whilst the above writers suggested that extensive semi-aridity had probably affected parts of humid tropical regions.

Global sea levels undoubtedly must have changed markedly in response to these climatic fluctuations, giving rise to important land bridges and allowing faunal migrations. In the low-latitude regions these climatic changes also had their dramatic effects. Indications of alternating periods of aridity and humidity in the tropics outside Southeast Asia are now abundant and well described (Tricart (1965); Frakes (1979); Flenley, Street-Perrot et al., Tricart, Williams in Douglas & Spencer (ed., 1985) and Douglas & Spencer (1985). Despite the promising evidence for climatic changes in northeastern Australia and Papua New Guinea, data concerning the Indonesian Archipelago is somewhat poor and paradoxical. Evidence indicating climatic fluctuations in the Indonesian and Malaysian region comes from various disciplines. Koopmans & Stauffer (1968) reportedly found geological remnants of strongly depressed snow lines in the Mount Kinabalu area in Borneo. Verstappen (1960) encountered similar features of lowered snow lines during the Star Mountains expedition in New Guinea. Further evidence for glaciations of high mountain ranges in Indonesia comes from Flenley & Morley (1978) with minimum ages of about 9,200 a BP and from Van Beek (1982) in the Gunung Leuser National Park (North Sumatra) who gives minimum ages of 7,600 a BP for altitudes of 3,100 m. Van Zeist (1983) in reviewing literature on altitudinal changes of forest limits and alpine vegetation zones in the Indonesian region and Papua New Guinea, remarks that many authors report significant lowerings of vegetation limits of at least 1,000 m during the last 30,000 years. Based on pollen analysis from the Sangiran dome on the foot slopes of the Lawu volcano in Central Java, Semah (1982) notices a decrease in arboreal pollen from Late Pliocene to Lower Pleistocene. She interprets the terrestrial environment around Sangiran at that time as dominated by an open vegetation, open forest and meadow, with some pollen species associated with a higher altitude. Jacob (in Bartstra (ed), 1976) concludes that based on faunal remains in the Sangiran area, the habitat consisted of grass- and woodland and that the climate was substantially drier and several degrees centigrade lower during the glacials than at present. Bartstra (1976) remarks that a certain type of mammalian fauna (grus grus) in the Upper Pleistocene terraces of the river Bengawan Solo hints at colder conditions than the present time. Palynological studies by Flenley (in Douglas & Spencer (ed), 1985) in Papua New Guinea confirm important lowering of the forest limit from altitudes of about 3,800 m at present to circa 2,100 m 17,000 years ago. An interpretation of the paleohydrological conditions for Queensland, northeastern Australia, during the last 123,000 years comes from Kershaw (1976). Based on pollen analysis he arrives at mean annual rainfall depths of about 500 mm for the period 80,000 to 10,000 BP compared with the 2,700 mm at present. Although human influence cannot be entirely excluded in his pollen record it is 'difficult to disbelieve the whole story' as remarked by Flenley (in Douglas & Spencer (ed), 1985). On the other hand many plant ecologists maintain the view that much evidence is available for Malaysia and Indonesia that rain forest has prevailed over the area for a long time and that the Quaternary climatic changes were not great.

Concerning the depression of temperatures during glacials, Chorley et al. (1984) state that during the last glacial stage (18,000 years BP), global temperatures were 3 to 6^{0}C lower than at present and ocean surface temperatures 2 to 3^{0}C lower. The sea level must have been at least 85 m lower. These authors argue that during this last glacial stage the tropics were substantially drier with humid tropical forests present as only shrunken remnants in a greatly extended area of tropical wet-dry savannah. The importance of global sea level lowerings are stressed by Verstappen (1974), remarking that vast shelf areas fall dry thereby strongly reducing the vapour supply areas. With reference to the Malaysian and Indonesian region Verstappen mentions three factors which are strongly related to climatic conditions during the Pleistocene glacial periods:

1) the position of the Intertropical Convergence Zone (ITC). This is closely associated with precipitation patterns and must have changed markedly during glacials;
2) the drop in land and sea surface temperatures, thus affecting the altitudinal zonation of vegetation;
3) conversion of the Sunda shelf into land during a glacial may have resulted in increased dryness in the bordering lowlands.

However, the magnitude of changes in temperature in the region of Southeast Asia is still under debate. Büdel (1957, cited by Verstappen, 1974) is inclined to the opinion that during Pleistocene glacials, a drop of only 1 to 2^{0}C occurred at ground level in the tropical rain forests. The sinking of the snow line to about 1,000 m in the Central Mountains of New Guinea and observations of a Pleistocene glaciation level at the top of Mt. Kinabalu on Kalimantan (Verstappen, 1974) contradicts the drop in temperature proposed by Büdel. The wealth of information collected during the last two decades on this subject points to global ground level temperature deviations for the last glaciation of 3 to 9^{0}C. Even larger deviations for ground level temperatures are surmised by Kraus (1973), who states that temperature drops of the equatorial oceanic waters were already in the order of 3 to 4^{0}C. Investigation of deep sea sediment cores indicates a drop of seawater temperatures of 3 to 5^{0}C in the equatorial regions during the glacials and a presumably higher seawater temperature during interglacials compared to present values. Gates (1976) applied the CLIMAP ice-age modelling program to the last glacial (18,000 years ago) and arrives at average global departures for the unglaciated land areas of 4.9^{0}C and 2.3^{0}C for the world oceans. Based on his map an average departure for the July air temperature was calculated to be 5.4^{0}C in the belt of equatorial areas within latitudes 10 degrees north and south.

It is evident that global sea levels fluctuated markedly in step with the drastic Quaternary climatic changes. Bloom et al. (1974) investigated marine shorelines in Papua New Guinea, yielding a reliable record of major sea level highstands over the last 140,000 years. A remarkably good correlation in time and relative altitude exists between high sea levels on Barbados and the oxygen isotope record from an ice core in Greenland (Frakes, 1979). However, discussions have not yet ended on the amplitude of the sea level changes. Verstappen (1974), based on a literature study, reports values between 70 and 100 m sea level depression in the SE-Asia region over the last glacial. Clark et al. (1978) calculate global changes in postglacial sea level and arrive at values of about 80 m. Geyh et al. (1979) sampled peat and mangrove deposits by vibrocorer in offshore sediments in the Malacca strait at depths of maximum 66 m below present sea level. The authors conclude that between 36,000 and 10,000 a BP the sea was eustaticly lowered to at least 40 to 60 m below present level. Older Pleistocene glacials may have lowered sea levels some 45 to 70 m, Biswas (1973) notices laterised surfaces in Older Pleistocene at depths of 40 and 92 m in punch cores in the South China Sea. Batchelor (1979) proposes sea level depressions of 180 and 130 m for the last two major glacials, respectively.

Notwithstanding debate on the exact amplitudes of sea level lowering, Verstappen stresses the climatological effects of transforming the shallow warm seas on the Sunda shelf into land areas. The accompanying effect must have been a considerable decrease in vapour supply, thereby increasing the relative dryness of the lowlands. Verstappen argues that even regional processes such as a shift of the ITC and conversion of vast shallow seas into land areas may influence meteorological processes in such a way that aridity could occur.

Recent investigations into climatic fluctuations of the Pleistocene have revealed data and evidence from many parts in the world which strongly suggest a global character for these fluctuations. Williams (1985) reviews the latest publications and findings. Moreover, he sketches the historical development of the idea among scientists that during the Pleistocene intervals of pronounced aridity have occurred even in the tropical lowlands, contrary to the long held view of ever stable tropical forest ecosystems since the Tertiary. Although the results of studies in Africa in the 1950s and 1960s indicated Pleistocene aridity, it was only during the last decade that the entrenched notion was rejected of glacial climates corresponding to pluvials in the low latitude areas. With respect to the Indonesian region the pollen analysis by Kershaw (1978), derived from Lynch Crater in northeast Queensland, Australia, indicates a remarkable reduction of annual precipitation from 2,700 mm at present to about 500 mm during the period 80,000 to 10,000 BP. Williams compares the inferred Late Pleistocene rainfall fluctuations with the paleotemperature curves from three deep sea cores and remarks that a causal connection appears to exist between lower equatorial oceanic temperatures and intertropical aridity. Evidence from deep sea cores, uplifted coral reefs in the Huon peninsula of New Guinea and fossil-bearing stratified loess in Central Europe demonstrates that glacial-interglacial cycles occurred of about 100,000 years duration. Interglacials seem to have lasted only about 10,000 years and Williams stresses the findings of Emiliani (1972) that sea surface temperatures in the tropics were as warm as, or warmer than today for only one-tenth of that time. To support the glacial-aridity relation in the tropics Williams (1975) lists the results of independent studies in South America, the Caribbean, the Middle East and from deep sea cores from the tropical Atlantic and Pacific. He concludes that all the studies point to a substantial rainfall reduction in the humid tropics during the last glacial maximum.

Another important aspect of glacial aridity appears to be the stronger winds during glacial times. Petit et al. (1981) examined ice cores spanning the last 32,000 years and conclude that at the end of the last glacial about 20,000 years ago the marine and continental aerosol inputs were respectively 5 to 20 times higher. Particle sizes from eolian dust in deep sea cores revealed the same effects (Sarthein et al., 1981). The latter authors conclude that the Trade winds were much stronger 18,000 years ago than today.

For the time being the paradox remains. Verstappen (1974) discussed at length the contrasting views held by botanists and ecologists, who maintain that equatorial rain forests existed uninterruptedly since Miocene times, and earth scientists who argue that strongly depressed snowlines, lowering of mean annual temperatures, lowered global sea levels leading to dry shelfs, fossil land mammals from open woodland-scrubs habitats etc., are indicative of considerable Quaternary climatic fluctuations. An acceptable compromise may be the view held by Verstappen (1974), who hypothesizes that the landscape and vegetation cover during a fully developed glacial with 30% drop in annual precipitation for the Indonesian Archipelago, consisted of vast plains covered by scrub and grass with relict clusters of rain- and monsoon forest. Lower precipitation, humidity and temperature and a pronounced seasonality were characteristics of the climate during glacials. According to the morphogenetic regions of the world (Chorley et al. (1984), this climate description falls into the category of tropical wet-dry climates. However, an extrapolation of results from the pollen study by Kershaw (1978), with a drop in annual rainfall down to about 500 mm in humid tropical northern Australia, indicates that the climate more closely resembled a semi-arid type. As will be shown in a next chapter with respect to field evidence, the climate during glacials may have been much drier than anticipated by Verstappen.

Riezebos (1984) discusses at length the relation between geomorphology and savannisation in the Upper Sipaliwini River basin in Suriname. Based on a savannah ecosystem approach by Sarmiento & Monasterio (1975), Riezebos summarizes the three main types of ecosystems which occur under tropical wet-dry conditions (1,2) and everwet tropical climates (3):

1) a seasonal savannah ecosystem under tropical wet-dry climates with well-drained soil conditions. In case of soils with higher water retaining capacities dry deciduous forest is present;
2) where waterlogging and water deficiency alternate during the year a hyper-seasonal savannah ecosystem is found;
3) under tropical everwet conditions a non-seasonal savannah ecosystem may occur on soils which are excessively drained and have low mineral status.

Riezebos associates the savannah ecosystem with wet and dry soil conditions, which is not necessarily related to tropical wet-dry climates. Nevertheless, tropical wet-dry climates will generally give rise to savannisation.

The above account attempts to demonstrate the ample evidence and data collected during the last two decades concerning Pleistocene climatic conditions. In particular a wealth of data comes from India, tropical Africa, South America and Australia. Regardless of the suggestions and postulations on Pleistocene climatic conditions, the field evidence from Southeast Asia and in particular the Indonesian Archipelago is still scanty (Besler, 1985, De Klerk, 1983, Van Beek, 1982). Much effort has been spent during fieldwork for this thesis to find geological or pedogenetic evidence in the Tertiary hills south of the coastal lowlands which indicates Pleistocene climatic fluctuations.

4.3.2 *Quaternary climatic conditions and coastal lowland development*

Obviously the sedimentary history of deposits underlying the present-day coastal lowlands is strongly related to the postulated Pleistocene climatic conditions. As stipulated by Verstappen (1974), the alternation of humid tropical climates with slightly cooler climates with pronounced long dry periods must have had deep impacts on the geomorphological processes. Whereas deep chemical weathering dominates in humid tropical climates, mechanical weathering gains drastically in importance in drier savannah-type climates. This results in the deposition of mainly clays and silts during humid tropical climates, like the present deposition of mud blankets in the Java Sea, and coarser clastics from physical disintegration during periods with a much drier climate. Fluvial incision by a distinct linear drainage system and thick soil development are characteristic for the humid tropics, whilst the development of planation surfaces by sheetwash erosion and diffuse ephemeral drainage systems with thinner and more regolith-like soils are more typical of drier conditions.

Table 4.2 Hypothetical sedimentary environments during the Pleistocene in North Java.

General characteristics	Humid Tropical	Tropical Wet-Dry Semi-humid	Semi-Arid
Annual precitation	> 1,800 mm	1,000-1,800 mm	300-1,000 mm
Number of months > 50 mm rainfall	> 11 months	5-11 months	2-5 months
Koppen classification	Af,Am	Aw	BS,BW
Weathering	Predominantly chemical producing clayey/silty suspended sediment loads	Alternating chemical and mechanical producing fine and coarse debris	Predominantly mechanical producing coarse angular debris
Morphological processes	Mass wasting by episodical slides on steep slopes; leaching and subsurface washouts	Sheetwash by high seasonal floods, rill and gully wash, channel flow and floodplain features Wind action	Sheetwash by high episodical floods gullying by ephemeral streams; Wind action
Morphology	Steep V-shaped valleys with sharp interfluves Wide valleys in lower reaches; Linear drainage pattern, high drainage density	Wide planation surfaces bounded by backward retreating steep slopes; Fe/Al crusts/staining faint interfluves Slopes with coarse debris Diffuse drainage pattern, braided stretches	Wide planation surfaces bounded by backward retreating steep slopes; talus slopes with coarse debris; pediments; Mn/Fe varnish on debris Ephemeral and episodic drainage systems
Vegetation cover	Rain forests and monsoon forests	Isolated clusters monsoon forests, mainly tree savannahs, seasonal cover by grass/scrub	Covered by grass/scrubs only during wet seasons

During a humid tropical period a coastal lowland landscape as developed during the Holocene can be expected, with mainly suspended river loads which are deposited as extensive mudblankets in the shallow Java Sea and during floods onto the very broad floodplain basins. Vegetation must have been very dense with vast backswamps and coastal swamps in the lower flood plains. Depending on the hinterland, only the larger river basins are capable of providing sands as bedload. These sands are deposited at the mouths of the rivers during flood discharges and carried off and further dispersed along the beaches by longshore currents. Onshore winds, which vary with the position of the ITC (Intertropical Convergence Zone), are particularly important in building up beach ridges and cheniers along the northern coast of Java (personal communication with Verstappen, August 1988).

A glacial period with a lowering of the sea level by tens of metres must have exposed vast areas now inundated by the Java Sea, covered then by a savannah-type of vegetation. Depending on the hinterland, alluvial aprons and veneers of coarser sands and debris must have been deposited during sheet floods and high river discharges. In this sedimentary scenery strata with low hydraulic permeabilities must have originated during humid tropical phases, with vice versa, the more permeable horizons during the glacial periods.

Viewed against the background of a savannah ecosystem classification by Riezebos (1984), based on soil moisture conditions at the end of the dry- and wet season, a vegetation formation typical for savannahs can be expected to have existed in the hilly hinterlands. During glacials an ecosystem can be expected in the coastal lowlands to have ranged from savannah to seasonal savannah on well-drained volcanogenic material and from seasonal savannah to deciduous forest on fine textured soils.

Table 4.2 summarizes the hypothetical sedimentary environments in the North Java coastal lowlands during the Quaternary. Assuming that the glacial periods have lasted much longer than the interglacials, it follows that deposition of the coastal lowland sediments during the Pleistocene must have mainly taken place under semi-humid to tropical wet-dry climatic conditions.

4.3.3 Geological evidence in the study area for Pleistocene climatic fluctuations

4.3.3.1 Introduction

Except for Engelen (1973), the present author did not succeed in finding literature or any publication in which geological evidence from Java is advanced in favour of climatic fluctuations. Some publications make mention of certain geological features which, with the present knowledge of Quaternary climatic fluctuations, may suggest formation under drier climatic conditions. Van Bemmelen (1949) refers to the 'plain of subaerial denudation of Kendeng' (p:569-577) in the Solo valley south of the Kendeng ridge in Central Java. The present author found the planation surface to have a very thin or generally absent soil, developed on Upper Kalibeng marls and calcareous mudstones (Upper Pliocene) near the town Gundih (south of Purwodadi) and in the broad valley of Purwodadi fringing the topographically higher anticlinal ridges. Van Bemmelen attributes a post-Middle Pleistocene age to this surface. Pannekoek (1949) mentions the same denudation level on both sides of the Kendeng ridge and argues that this level of planation dates from the upper Pleistocene and has been formed in an 'astonishingly short time'. However, he explains formation of the planation level merely by peneplanation processes[7]. His geomorphological map of West- and Central Java also shows flat plateaus in the morphological Northern Zone. The

7 Conspicuous are the gravel deposits or remnants of gravel deposits on these planation surfaces (Pannekoek, 1949) which are difficult to explain as simple river gravels. The gravels on the Kendeng planation level are still under debate. There are also gravels on high terraces in the Kumbang area (kabupaten Brebes) and on the Lengkong surface in West Java.

geomorphological maps of the Serayu Valley by Karmono Mangunsukardjo (1984) show similar planation surface remnants.

In this section a number of rock exposures will be described which are thought to contain convincing evidence for climatic fluctuations during the Pleistocene. Most of the outcrops are located in the kabupatens Brebes and Tegal, which merely reflects the selection of field project areas. However, exposures with similar geological features in the kabupatens Cirebon and Indramayu will also be briefly reviewed.

4.3.3.2 Extensive surfaces of low relief

Areas favourable for the search of planation surface remnants are those with Lower and Middle Pleistocene volcanic rocks not hidden by series of younger volcanics. Such areas are present about 40 km west of the city of Semarang along the road Weleri to Temanggung. In particular, south of the town Weleri sets of low-relief surfaces are present separated by cliff-like escarpments in the volcanic Damar Formation. In a previous chapter pertaining to geological structures along the southern border of the northern coastal lowlands, attention was paid to the regional step faults and marginal flexures cutting a former planation surface. Just before the Damar river enters the coastal lowlands the stream has incised at least two planation surfaces, the remnants of which are found on top of the interfluves. The section along the Damar river clearly exhibits the step between the two levels. These planation surfaces belong to one planation level of about 110 to 200 m which can be widely recognized in the surrounding area. In fact three regional levels can be discerned (see also Fig. 4.5f), viz. one level at about 30 to 50 m near the coast and within the coastal lowlands, the second level at 100 to 200 m often covered by an alluvial veneer of volcanogenic materials and a third level ranging from 400 to more than 500 m.

> In his explanatory notes of the Semarang-Ungaran area further to the south Van Bemmelen (1941) mentions 'steep cliffs' about 100 m high in this area which are covered by talus deposits and landslides according to the geological map of the quadrangle Magelang-Semarang by Thaden et al. (1975). The central Ungaran volcano complex is said to be surrounded by a breccia plateau of the Old Ungaran. However, the same slightly undulating landscape trends further towards the east and is easily recognized in the areas south of Weleri, far from the Old Ungaran eruption centre. This extension towards the east does not agree with the idea of a volcanic foot plain. Van Bemmelen further mentions the 'Tjandi hilly region' (the Damar series south of Wèleri) and describes it as a '4-8 km wide strip of irregular hills and ridges of about 100 m height'. The escarpment flanking this planation surface on the northern side bears features of marine abrasion with fossil notches. Along the river Kali Kuto, north of Weleri, the present author found carbonaceous near-shore clays underlying fluvial deposits from this river. This clearly indicates that the sea once reached the cliffs, presumably at its peak level about 4,500 a BP.

Nevertheless, the main driving mechanisms behind these cliff-like escarpments are Quaternary tectonic movements along sets of normal faults or marginal flexures, which gave rise to a staircase-like topography. The extensive surfaces of low relief with a gentle and undulating topography are clearly cut off by the step faults and hence must be older. They are in all likelihood not produced by lateral fluvial erosion or by peneplanation processes. The following arguments can be put forward to oppose a stream-made topography:

1) the peneplain concept is not applicable for the Quaternary in this highly unstable orogenic area. Periods of tectonic stability of 10 to 50 Ma necessary to develop peneplains (Chorley et al., 1984) are not realistic along active plate subduction zones. In addition, the huge amount of volcanic material produced during the Quaternary interrupts any Davisian cycle of erosion;
2) a glance at topographic maps of the northern part of Java reveals that none of the larger rivers is presently capable of developing a broad valley by lateral erosion;
3) according to the now outmoded Davisian model peneplains should develop by the spread of graded conditions headward up the tributaries. However, in the present-day geological setting of Java, during humid tropical cycles, no degradational plains of vast extent exist near the present base level of erosion; all topographical plains near the coast are aggradational plains. The flood plains adjacent to the larger rivers in the erosive hinterlands constitute but a small portion of the total area of low relief surfaces.

If not formed by peneplanation processes then what other geomorphological mechanism might be capable of producing such vast surfaces of low relief? Most textbooks on geomorphology do not offer more than the peneplain concept on the one hand and the extraordinary arid pediments on the other. In the area of Weleri it is unlikely that the planation surfaces originated as low relief volcanic foot slopes. The arguments to support this view are the facts that the surfaces are developed both on different volcanic formations and on Miocene and Pliocene rocks. Furthermore, the original eruption centres of the Lower Pleistocene volcanoes near Weleri were arrayed on an E-W trending volcanic zone most likely through the Proto Ungaran volcano of Van Bemmelen (1941). The planation surfaces cut through these old eruption centres (remnants of pipe conduits and cinder cones). These fossil volcanic vents and pipes filled with friction breccias are found along the main road Parakan-Weleri, north of the village Sukorejo to 2 km south of Weleri.

Planation surfaces as exposed south of Weleri are found in a broad strip along the boundary hinterland and northern coastal lowlands. In particular the planation levels of 30-50 m and the higher one from 100-150 m are found as typical low relief surfaces or as hill summits. However, recognition is frequently obscured by severe erosion in the hinterlands leaving merely a few hills with their summits still touching one of the surfaces. Remnants of the planation surface with an altitude of about 100 to 150 m are reasonably well preserved in the hinterlands, especially on Tertiary strata.

In the area of kabupaten Tegal, near the geological cross section shown in Fig. 4.5e and the reservoir Waduk Cacaban, the planation surface of about 100 m is still widely recognizable on the Miocene Halang and Rambatan Formations. The surface is locally covered by young fluvially redeposited volcanics. As elaborated in a later chapter, the volcanic deposits consisting of lahars and volcanic material redeposited by water action give the impression of being laid down on a low relief surface which is now dissected. The same can be said of the young volcanics Qc east of the river Kali Rambut, which appear to have been deposited on the planation surface of 30 to 50 m developed on Pliocene beds. The young volcanics Qc are exposed in the channel of the Kali Rambut, 2 km north of the village Gongseng (see Fig. 4.1), and consist of consolidated laharic deposits unconformably overlying clays of the Upper Pliocene Kaliglagah Formation. These deposits are apparently absent upstream suggesting an east to west flow direction.

The presence of a higher level remains uncertain though many summits further south reach altitudes of 500 to 600 m.

Further west in the area near Waled (in the vicinity of cross section Fig. 4.5c) the same level of about 100 m is well expressed on the Halang Formation bordering the river Cisanggarung. The ridge just south of the coastal lowlands, which consists of strongly upthrusted Pliocene strata through which the river Cisanggarung has eroded a water gap, fits remarkably well into the level of about 100 m. This level appears to extend laterally on the volcanic Gintung Formation exhibiting a conspicuous flat surface. A beautiful view of the area is offered by standing on the ridge of upthrust Pliocene strata near the water gap revealing the level at about 100 m. Near the reservoir Waduk Melahayu similar surfaces of low relief at about 100 m altitude can be found.

Good examples of a staircase-like topography are offered by the hill range built up by the Gintung Formation from Cirebon to the village Sindanglaut. Approaching the hill range from the lowlands reveals a planation surface, stripped from a soil, at the bottom of the streams in the vicinity of the Bumiayu-Cirebon railway. Clayey sands of the Holocene piedmont deposits overlie this surface elevated at about 10 m. A broad planation level at 20 to 40 m, with a partly exhumed soil cover, is omnipresent in the hills bordering the lowlands. Towards the south an abrupt break of slope connects this surface to a much less developed surface before an escarpment is reached leading to the highest level of 100 to 150 m.

West of the river Cimanuk in the southern part of kabupaten Indramayu, near the cross section of Fig. 4.5b, the planation surface with an elevation of about 100 m is present in the Tertiary Subang Formation Msc as numerous table hills. Although strongly dissected the residual hills lie with their summits at this surface. Analogous to the situation in the hinterlands of kabupaten Tegal, the table hills are veneered with redeposited volcanic materials which upon erosion slump to the present river and creek valleys forming a kind of 'misfit' channel lag deposit. These channel lag deposits are rather coarse with dm-sized boulders and angular fragments, which are apparently difficult to transport by the present brooks. On his geomorphological map of Java Pannekoek (1949) interprets this area as a flat plateau.

The same plateau-like topography is continued on the Subang Formation near the town of Subang in the vicinity of geological cross section Fig. 4.5a. Conspicuous is the presence of folded Tertiary strata at shallow depth under the Late Pleistocene volcanic fan material of the coastal lowlands, obviously separated by an unconformity. The geological map (1:50,000 scale) of Silitonga (1973), clearly reveals many small exposures of the underlying Subang and Citalang Formation along brooks in the coastal lowland area. Furthermore, it is striking that this plateau-like surface beneath the Late Pleistocene volcanic fan deposits is again found at elevations of about 100 m. The road from Subang to the west, through the villages Kalijati, Cipendeuy and Cempaka to the town of Purwakarta, is located upon this planation surface and clearly reveals the low-relief nature. This plateau under southern parts of the coastal lowlands is also indicated by Pannekoek (1949) on his geomorphological map. In his geological field report Koolhoven (1934) mentions the same 'terrace' of folded Neogene strata under the 'Prahoe tuffs'. Pannekoek goes even further and considers this plateau to extend eastwards as far as Tomo. The present author examined the deeply incised river valley of the Cipanas near the village Cikawung (16 km NW of Tomo) and could not locate such Tertiary deposits as the Subang and Citalang Formations. It must be admitted that the elevation of the examined site is about 80 m and the incision by the

Cipanas river may therefore not be deep enough to reach the underlying plateau, expected at altitudes of 30 to 40 m. However, river sections between Tomo and Ujungjaya, from the road to the hill range, give the impression of a plateau-like surface eroded in the steeply north dipping Citalang beds covered by Holocene clayey sands. This surface may be passing into the surface on top of the Late Pleistocene Volcanic Fan Formation, widely exposed in the southern parts of the lowlands in the kabupatens of Karawang, Subang and Indramayu.

4.3.3.3 The Significance of Volcanogenic Gravels in the Hinterland Catchments

Field surveys in the smaller river basins situated in the hinterland belts near the coastal lowlands always reveal important gravel deposits along the river and brook valleys. At first sight these gravel deposits remain fairly unnoticed. They consist mainly of cm- to dm-sized sub-angular volcanic boulders, angular fragments of limestones and minor mudstone- and tuffaceous sandstone pebbles representing autochtonous erosion materials from stream undercutting. However, the significance of the volcanic pebbles and boulders is much greater than one first realizes. Particularly in smaller catchments (for example west of cross section Fig. 4.5e) which are underlain entirely by Tertiary clayey strata these unweathered volcanic gravels are wholly allochtonous. Since the present drainage divides of many of these catchments lie near the coastal lowlands, the question can be raised of how the volcanic gravels ever entered the catchments. As already described for the area near Tomo in the south of kabupaten Indramayu, young redeposited volcanic rocks are still found as remnants on the planation surface at about 100 m altitude. This might then be the clue to unravel the presence of the volcanic gravels in these catchments. The most plausible explanation is that the gravels must have been deposited on a higher surface which was subsequently dissected thereby causing the gravels to slump and slide into the newly formed river valleys. As was noticed in the Tomo area the gravel size and in particular the boulders are perhaps too large to be transported as bedload in the smaller catchments and in all likelihood represent misfit gravel deposits. One may contemplate further the nature of the surfaces upon which the volcanic gravel deposits must have been deposited. Transport of volcanic clastic materials must have taken place by either braided or meandering stream action, and by a second very important transporting mechanism, namely volcanic mudflows (lahars). If this rationale is adopted than the following logical outcome must be to accept that a more or less low relief surface must have existed upon which these fluvio-volcanic deposits may have spread over vast areas. The area in kabupaten Tegal, E and SE of the reservoir Waduk Cacaban, offers particularly good examples of extensive volcanic deposits on the planation surface at about 100 m elevation.

In his field survey report of the area near the rivers Ci Pemali and Ci Gunung, west of the volcano Slamet in the kabupaten Brebes, Ter Haar (1928) is also astonished by the presence of these gravels in the stream beds. He describes the area as a gently undulating hilly landscape at an altitude of 100 to 150 m. He notices that these volcanic gravels occur in every river valley. He also mentions that the highest elevation of gravel terraces is found along the river Cigunung at about 125 m.

Other conspicuous occurrences of volcanogenic rudaceous deposits are found in the hilly Tertiary area bounded by the Kumbang breccias and the geological cross sections, of Fig. 4.5c and Fig. 4.5d (see Fig. 4.4) in the southern part of kabupaten Brebes. The geomorphology of this folded area, exposing mainly Miocene rocks of the Pemali, Halang and Kumbang Formations, can also be described as a gently undulating hilly landscape area ranging from 100 to 200 m in altitude. It gives the impression of a planation surface, dissected by present drainage systems, in which isolated symmetrical hills of Kumbang breccias and sharp NW-SE trending ridges of steeply dipping upthrusted tuffaceous sandstone beds in the Halang Formation are the remaining morphological elements. Those higher parts not yet eroded by the drainage systems are invariably covered by volcanogenic rudaceous deposits. Pannekoek (1949, p:304) notes these 'high terrace gravels' on the geological sheet Majenang, scale 1:50,000 by Kastowo (1975). The present author further investigated these cobble and boulder gravels with the following results. In many outcrops the coarse rudites comprise boulders of up to 50 cm and cobbles in a clayey coarse sand matrix. Pebbles are few in number, though a decrease in fragment size can be noticed in a northerly direction. Near the Kumbang ridge in the south, thicknesses of the boulder gravels exceed 10 m. The clasts are matrix supported and lack any grading in fragment size. Cross-bedding, laminations and fine sand or silt laminae resulting from flood recession stages are also completely absent. Stratification in either the boulder and cobble arrangements or the sand matrix is hard to recognize in these extensive massive beds and neither lenticular units, cut-and-fill structures nor former stream channels have yet been found. In outcrops where the underlying Pemali or Halang beds are exposed, thin partly exhumed paleosols are evident. The rounded to sub-angular clasts consist invariably of bluish-coloured dense andesites from the mountain range in the south, which is built up by Kumbang breccias. In upper parts of the deposits the sandy matrix has generally been weathered to yield reddish to deep red colours in which pebbles can be easily pulverized by hammer blow.

Standing on one of these terrace remnants near the Kumbang ridge, the presence of these weathered cobble and boulder gravels can be easily recognized by the flat terraces on interfluves and the reddish colours. One gets the impression of a slightly northward dip of the terrace system. The deposits are in fact much more extensive than indicated on the geological map of Majenang (Kastowo, 1975) and field observations show no relation between this terrace system and the present alluvial deposits. The sedimentology of the cobble and boulder gravels excludes deposition by stream action, since the coarseness of the fragments and the absence of upward fining units, cross-bedding and fine sand laminae suggests deposition in the proximal and midfan facies of extensive alluvial fans, presumably partly as high viscosity mudflows. The materials have obviously been derived from the impressive Kumbang ridge in the south. Fans must have advanced over an extensive surface of low relief on Pemali and Halang strata, younger than the Linggopodo deposits of the old Slamet volcano.

A similar mechanism of advancing volcanic fan lobes, far from the old Slamet volcano over low relief surfaces, is also thought to have occurred for the older Linggopodo layers. Remnants of Linggopodo deposits are found on old erosion surfaces in the Kumbang ridge near the Bentarsari depression, west of the town Bumiayu.

The present author considers the presence of these volcanic gravels in small catchments on Tertiary marine rocks and the widespread cobble and boulder gravels to be strong arguments in support of the planation surface theory.

4.3.3.4 The Prupuk reef limestones

One of the most conspicuous outcrops with features of climatic fluctuations was encountered in a quarry of Lower Pliocene Tapak reef limestones near Songgom. Emerging as culminations above the Late Pleistocene Balapulang volcanic fan the quarry is situated 25 km SW of the town Tegal. The best exposures are found at the southeastern side of the quarry by entering the site from the village Kedawung. At this side the underlying crystal tuffs of the Lower Pliocene Tapak Formation are exposed with bedding dipping 60^0 toward 180^0. The rapid transition from tuffs to the reef limestones is remarkable. The tuffs obviously fell into the sea and the gradually increasing number of mollusca shells points to decreasing volcanic activity. Corals appear, increase rapidly in number in an upward direction until finally reef building organisms prevail. The recrystallized coral limestones exhibit a fairly uniform lithology and some primary porosity. Locally calcarenites are present with burrows.

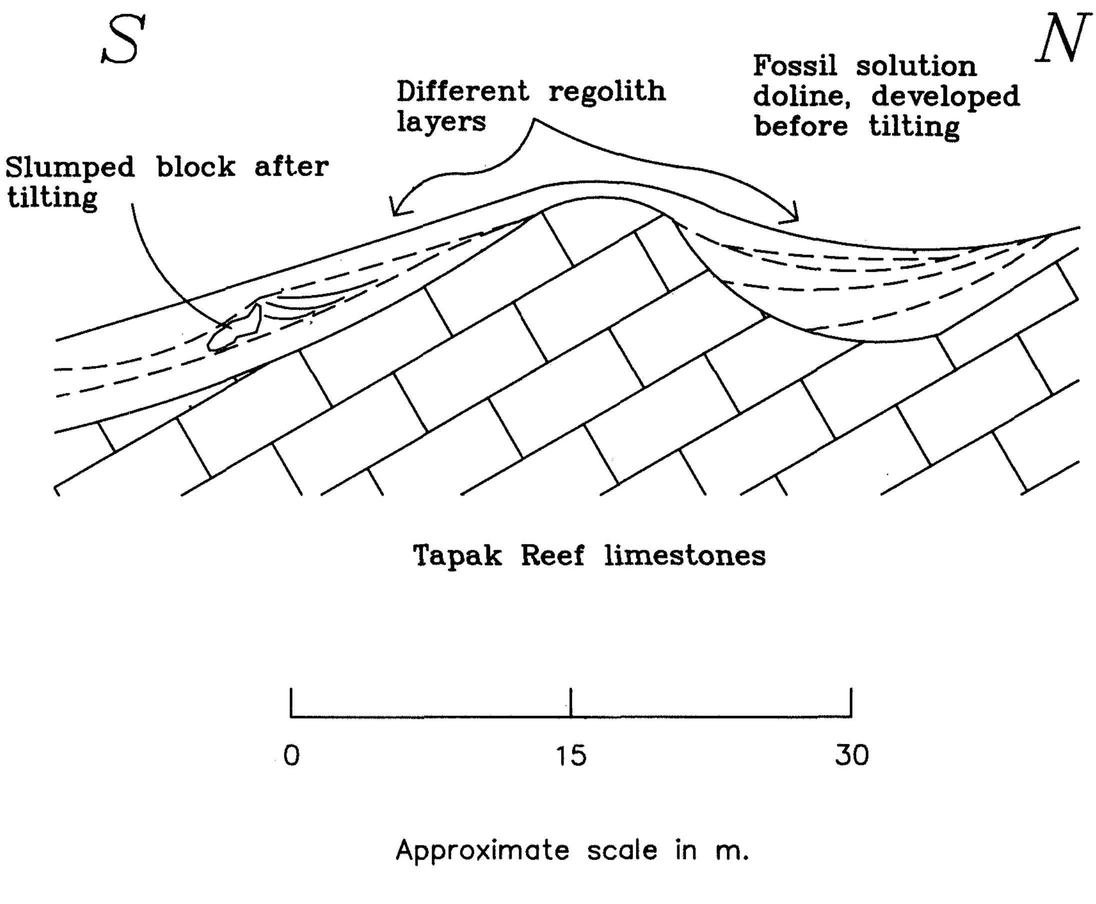


Fig. 4.6 Field sketch of tilted reef limestones at Prupuk.

A significant feature of the reef limestone outcrops is the occurrence of an omnipresent cover of mantle rock which attains thicknesses of 1 to 4 m. This mantle rock consists entirely of angular fragments of limestone, sizing 1 to 5 cm. Concave upward layering in the mantle rock with thin soil horizons indicates talus slopes. The angular shape of the fragments must have been the result of physical disintegration, a process not expected to take place during a humid tropical climate. Many exposures in the quarry show the presence of a fossil karst system with dolines and other solution features filled with the mantle rock.

Depending on current excavations in the quarry, complete sections of the limestones are occasionally exposed and show a paleo-karst scenery of conjugate patterns of clefts and ridges covered by a terra rossa-like clayey soil up to 50 cm thick. This paleosol presumably originated in hot humid tropical Pliocene climates and is overlain by the light coloured regolith. The terra rossa-like soil appears as cm-thick streaks in the overlying regolith, apparently as a result of reworking by demolition and slumping of the reddish tropical soils during the regolith formation. Many angular unconformities on an outcrop scale occur in the regolith, are indicative of the colluvial character[8].

Another remarkable aspect in many of the outcrops in this Prupuk limestone quarry is the presence of small scale faults, which clearly cut through the layers in the regolith and are in turn overlain by undisturbed layers. These syn-sedimentary faults have a generally E-W trend and indicate tectonic movements during formation of the mantle rock.

Within the mantle rock many distinct angular unconformities with erosion surfaces and faint soil development are present suggesting tectonic movements. The fossil karst system with the large diameter dolines and sinkholes clearly predates the tilting and folding. The field sketch of Fig. 4.6 shows a N-S section in one of the quarries in the southeastern part.

A former large doline, developed before tilting of the limestone mass, is filled with the mantle rock and exhibits many unconformities and distinct differences in dip of the regolith layers. A large limestone block obviously broke off and slid downwards along the regolith talus slope as a reaction to tilting. The block is buried by a younger set of regolith layers with a different dip. The various stages through which the Prupuk reef limestones developed in the Neogene are shown pictorially in Fig. 4.7.

A number of important conclusions can be drawn from the geological features of these Lower Pliocene reef limestones:

1) the development of the paleo-karst system and formation of the terra rossa-like residual soil took place before tilting and folding of the Tapak Formation. The paleosol was developed under hot humid tropical conditions, presumably during the end of the Pliocene;
2) the omnipresent mantle rock with angular limestone fragments originated as talus under Pleistocene climatic conditions during which mechanical rock disintegration was dominant. These climatic conditions must have been either tropical wet-dry or, even more likely, semi-arid;
3) tectonic movements took place during the formation and deposition of the mantle rock.

---

8 Exactly similar features of mantle rock layers with angular fragments, small-scale angular unconformities and fossil dolines filled with former soil materials, wood remains and fine sands with well-rounded grains suggestive of eolian transport, have been found by the present author in Pliocene (?) limestones on the southern limb of the Rembang anticlinorium (near the village of Sendangharjo along the road Blora-Rembang).

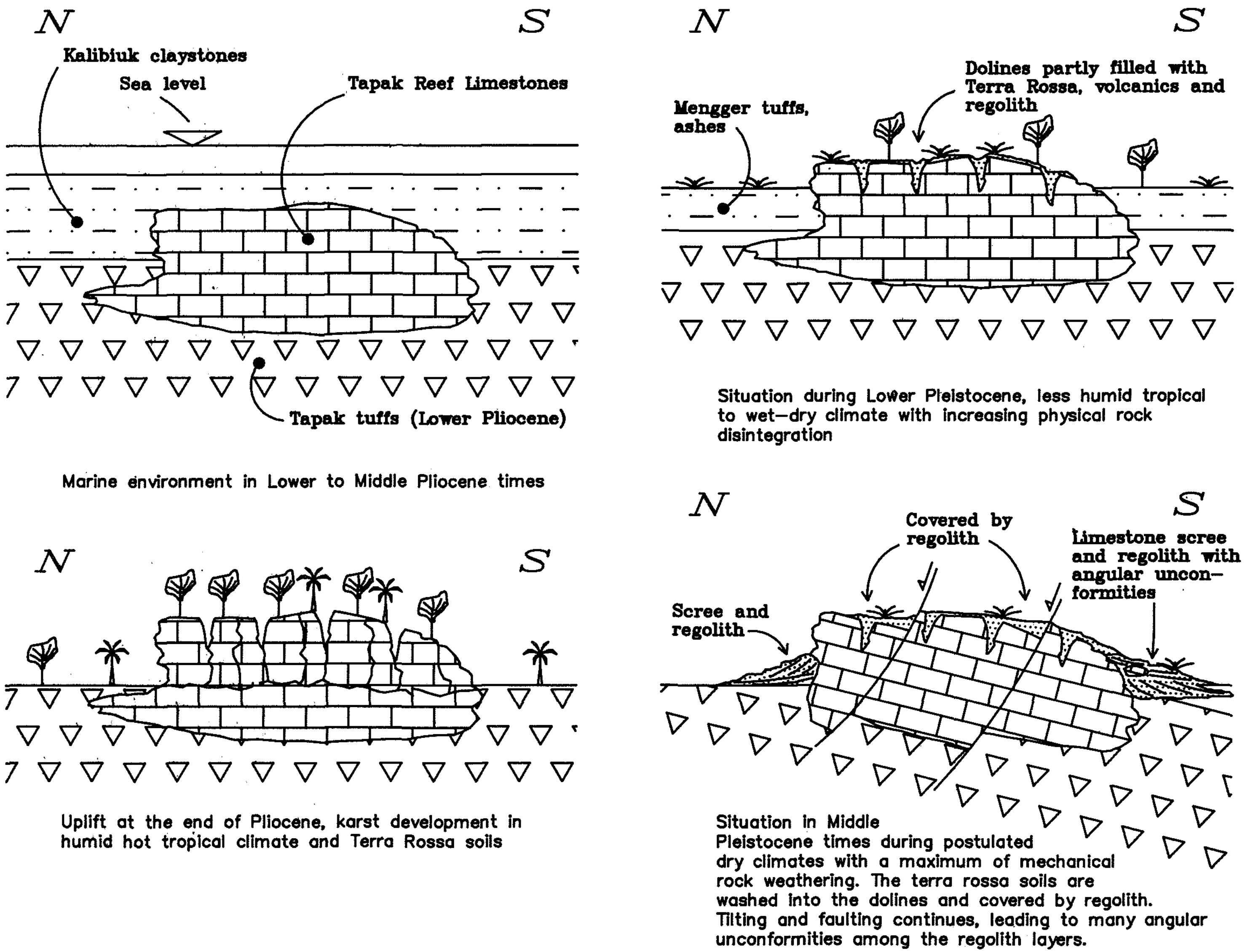


Fig. 4.7 Schematic representation of the various stages of the Prupuk reef limestones.

4.3.3.5 *The low-relief surface on the Gintung Formation in Cirebon*

An interesting surface of low relief with great lateral extent is present on the Lower to Middle Pleistocene fluvio-volcanic Gintung Formation in kabupaten Cirebon. The surface is best developed west of the river Cisanggarung at about 8 km SW of the village Waled. Good exposures of the Gintung Formation and the relation with the low-relief surface are found on the flanks of the remarkable isolated table hill Puter Lumbung. The top of the steep hill[9] is completely flat and fits well into the surface which lies at about 130 to 160 m. The Gintung Formation as exposed on the flanks of the hill and in deeply incised valleys in the vicinity. It consists of cross-bedded coarse sands and cm-sized sub-angular pebbles in monotonous sequences of cut-and-fill sets with a height of only a few decimetres. In suitable exposures the sets can be followed over tens of metres. Each set of cross-bedded sands is overlain by thin horizons of fossil soil with iron hydroxides and Fe-Mn stained pebbles. Clays and silts are absent in the cross-bedded sets. Sedimentary structures in the exposures give the impression of a pebbly braided stream environment as found in the middle reaches of alluvial fans.

The geological significance of Puter Lumbung hill is not the lithology of the Gintung Formation, but the nature of the low-relief surface on top. Should the plain on top be considered as an original aggradation surface and thus a former landscape during deposition of the Gintung Formation, or as a secondary destructional surface? The following arguments are considered to be indicative of a denudational surface:

1) the soils on top of the surface are very thin or absent;
2) the remarkable 'flatness' of the surface as distinct from the concave landscapes on volcanic fans;
3) the surface dips slightly to the north, whereas the Gintung beds appear to dip to the south. This southward dip of the Gintung beds might be explained by backward rotation as a result of upthrust movements along the regional fault structures near Waled;
4) apart from the younger cover of volcanics from the Ciremai volcano further towards the west no other deposits were found on the surface.

4.3.3.6 *The Late Pleistocene Volcanic Fan Deposits in the Coastal Lowlands of West Java*

Although treated in more detail in Chapter 6, the lithological characteristics of the Late Pleistocene volcanic fans, exposed over vast areas along the southern periphery of the coastal lowlands in West Java, attract attention from a viewpoint of unravelling the paleoclimates. In contrast to the coastal lowlands of Central Java, the lowlands in West Java are formed by a broad strip of red to brown coloured Late Pleistocene fluvio-volcanic coalesced fans. In the field this easily mappable lithological unit appears as a monotonous low-relief surface bordering the Tertiary hinterland, traceable by its red colours up to the medial parts of the coastal lowlands. Water well drillings indicate that the unit extends far to

9 The top of the table hill can only be reached by a steep narrow foot path from the south. A view from the top reveals the surface stretching far to the west and southwest with a general slightly northward dip.

the north and presumably under the present Java Sea. The top surface of the unit is interpreted as being a former landscape during the low sea levels of the last glacial period. Rimbaman et al. (1986) carried out auger hole drillings near the coastline in kabupaten Karawang and report the pre-Holocene substrate to consist of red to yellow mottled fine volcanic sediments, occasionally with the mineral jarosite and frequently with layers of small pebbles. Concretions of iron, manganese and lime occur and plant remains were found. These soil remnants are indicative of oxisols which are formed during climatic periods with pronounced seasonability (De Goffau & Van der Linden, 1982). Fluctuating groundwater tables resulting from an uneven distribution of annual precipitation and high temperatures are necessary to produce such plinthite soils. De Goffau & Van der Linden mention that oxisols may also be found on old erosion surfaces.

The depositional environment has been interpreted by Rimbaman et al. (1986) to vary from eolian and fluviatile to marine. The fluviatile deposits resemble alluvial fan deposits. Verstappen (1974) reviewed literature on sediments of the Sunda shelf and notes the mottled or spotty red clay horizon featuring desiccation, oxidation and soil formation below the Holocene marine clay blanket. Hehuwat (1972) shows a map of the relict sediments on the Sunda shelf, revealing sands and sand muds north of West- and Central Java.

All these features such as the eolian character, the alluvial fan-like environment far from the hinterland, the coarse relict sediments and type of soil formation point to conditions which are not met during the Holocene. The original Holocene sedimentary environment, prior to major human disturbance by canalization, consisted of coastal lowland outward building by deposition of suspended clays in the flood plain basins and extensive clay blankets in the Java Sea.

4.4 *Discussion and Synthesis*

In this chapter the general objective was to unravel the geological development of the hinterland in terms of major Pleistocene events, geological structures and geomorphological characteristics, which might in turn be extrapolated to the Quaternary lowland basins. The rationale behind this chapter is that developments on a regional scale in the hinterlands are thought to be reflected to a certain extent in the Quaternary sedimentary basins north of Java. This accords with the general approach followed in the thesis to depart from hierarchical frameworks of large scale at higher levels and to descend along the lines of hierarchy to lower levels.

Attention in this chapter was mainly directed to tectonic structures in the hinterlands bordering the coastal lowlands and the peculiar geomorphology of extensive surfaces of low relief separated by cliff-like escarpments. Encouraged by the findings of Engelen (1973) and Verstappen (1974), much effort was directed to finding geological evidence which may support the hypothesis of significant Quaternary climatic changes, even on the island of Java. The present author is inclined to the opinion that the geological evidence of the regolith mantle found around the reef limestones of Prupuk and Blora-Rembang and the widespread presence of volcanic gravels in small catchments on Tertiary rocks is most convincing. In addition, the extensive surfaces present in the area west of Semarang provide further support. As previously argued, the now outmoded concept of peneplanation is not applicable in such young orogenic areas as Java. The wealth of data collected by various disciplines in recent years from humid tropical areas strongly indicate the presence of profound climatic changes during the Quaternary and moreover, stress the effect of drier and perhaps also colder and windier climates on morphological processes of landform development.

Based on investigations in this thesis it must concluded that the morphological development of the hinterland along the northern coastal lowlands is a complex and intricate interaction between tectonic gravitational gliding movements on a regional scale and the repeated effects of drier climates during which the extensive surfaces of low relief were shaped. The beach rocks and the angular unconformities in the regolith mantle of the Prupuk reef limestones are considered as convincing evidence of more or less continuous tectonic movements since the Pliocene-Pleistocene boundary.

The consequences for structures beneath the Quaternary coastal lowland deposits are now obvious with this tectonic framework of almost continuously gravitational outward gliding of incompetent rocks along décollement zones, situated near an important tectonic hinge zone of the rising Java geanticlinal and the subsiding foreland basins. The effects of climatic changes and strongly fluctuating sea levels during the Quaternary must also have had their effects on the sedimentary basin filling. Fig. 4.8 presents general tectonic structures in the hinterland and the system of low relief surfaces with relevant features of marine abrasion remnants and veneers of volcanic materials.

Reconstruction of the hinterland Quaternary geological evolution and the building of a sediment pile under the present-day coastal lowlands is not straightforward in the light of alternating glacial and interglacial periods; each has a different impact on the morphogenetic development and added to this the complexity of a more or less continuous tectonic movement. Nevertheless, a general reconstruction is attempted on the basis of field data and the morpho-tectonic model of Fig. 4.8.

Starting at the end of the Pliocene, the coastal and hinterland areas must have comprised a vast marshy coastal lowland with dense vegetation. The Java geanticline must have started to rise, particular in the west. Climatic changes may have already started early in the Lower Pleistocene, as indicated by the Kali Glagah mammalian fauna. The first major sea level lowerings must have also begun, pushing the ETA systems to the north. Volcanism was limited to some local eruption centres, principally in Central Java, constituting an additional sediment source to that already provided by erosion products of the Upper Pliocene Formations.

Tectonic movements of outward gliding gained in importance in West Java and the development of a major décollement zone was in full swing. The gradual rising of the geanticline, compensated by en-échelon normal faults gave rise to formation of the Quaternary sedimentary basins. In Central Java the geanticlinal rise and formation of en-échelon normal faults was somewhat delayed compared to West Java. The Lower Pleistocene covers a time span long enough for at least two major glacial periods. The morpho-dynamic aspects of these periods remain uncertain. Viewed against the upheavals following the Lower Pleistocene it stands to reason to assume that the remains of former planation levels are obliterated by erosion. As volcanism in the Lower Pleistocene was far less abundant than in the Middle Pleistocene, it is expected that source rocks for coarse materials to be deposited in the sedimentary basins of the coastal lowlands during glacials have also been limited. This implies that the Lower Pleistocene sediments may have been predominantly fine-grained.

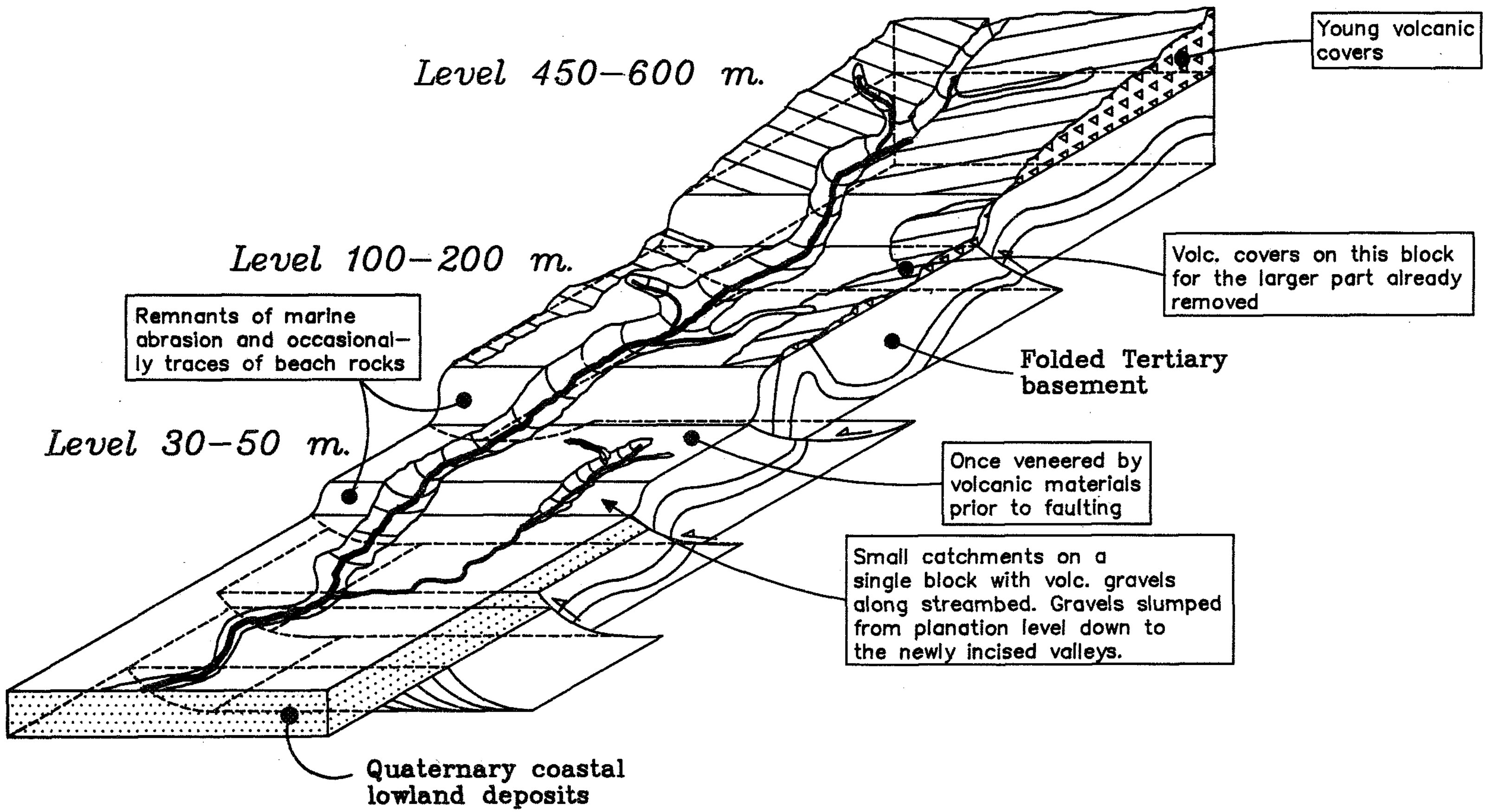


Fig. 4.8 Diagram showing the interaction of tectonic movements and the system of extensive low-relief surfaces.

The Middle Pleistocene was a period of turbulent events such as the building of the volcanic backbone of Java. The effect must have been felt in a further major uplift of the geanticline along reactivated en-échelon faults in the tectonic hinge zone and the building of a row of mutually contiguous volcanic cones. Extensive volcanic fans may have been built and may have reached far to the north during drier periods with low sea levels. The major building of the sediment pile in the basins is thought to have taken place during the Middle Pleistocene. The possible remnants of planation surfaces developed during the Middle Pleistocene should be searched for under the Notopuro and Linggopodo beds. The present-day remnants of planation surfaces depicted in Fig. 4.8 are thought to originate from Upper Pleistocene times. Referring to Fig. 4.8, the beach rocks are interpreted as last interglacial, implying that the fault between the level of 30-50 m and the level 100-200 m must then have been concurrent with the same interglacial or slightly earlier. It then follows that the planation surfaces must have been developed during an earlier glacial. The vast volcanic fan as found underneath the coastal lowlands in West Java originates thus from the last glacial period.

V. REGIONAL PLEISTOCENE STRATIFICATION IN THE COASTAL LOWLANDS

5.1 Introduction

The study of groundwater systems in the Quaternary sediments of the northern coastal lowlands of Java is largely impeded by the scarcity of sub-surface geological data. Formally, all borehole sample descriptions and geophysical logs of water wells throughout Indonesia have to be filed in archives of the Directorate of Environmental Geology in Bandung. The water well archives already date from pre-war times. In those days many well drilling reports were published in the annals of the mining department such as the 'Jaarboek van het Mijnwezen'.

Deep water wells drilled in the pre-war days, although accompanied by lithological descriptions of the borehole samples, do not provide much conclusive geological information. The impression is gained from the lithological descriptions of merely visual examinations carried out by drilling crews, presumably unskilled in lithological descriptions of samples. It implies that much significant sedimentological information may have been overlooked. The same applies to the downhole sample descriptions of the large diameter water wells drilled during the last two decades. Lithological descriptions, if available, are generally of poor quality hampering further interpretations. However, some detailed lithological and micro-paleontological investigations on borehole samples are available for a water well in Jakarta (Marks, 1956) and two wells near the town Pamanukan in kabupaten Subang (Djoehana, 1984). The generally poor lithological descriptions are associated with the drilling techniques, which consist mostly of jet drilling for even the larger diameter wells. A steel casing follows the drill bit with the drilling fluid flowing upwards in the annular space around the drill pipe. The cuttings are carried upwards in suspension and collected at the casing collar; reasonable samples may be obtained when drilling proceeds carefully. However, for most contractors the objective is a producing water well and sample collection, even when stated in the contract, is a matter of secondary importance. It should be evident that the quality of the samples and the field descriptions are poor and the depth provenance is doubtful.

Boreholes penetrating the entire Quaternary sedimentary sequence to strata interpreted to be of Pliocene age are found in the Jakarta area (Soekardi, 1972). Depths to the assumed Pliocene strata are in the order of 300 m. The general impression gained from the various drilling reports is an unconsolidated rock pile built up of predominantly clayey and silty sediments in which silty sands occur apparently as randomly distributed thin layers. The silty sand layers vary in thickness, usually not exceeding 2 m. The number of sand layers, apparently without any lateral correlation between adjacent boreholes, is usually much fewer than ten. The apparent absence of any lateral correlation or zoning, as judged from the lithological descriptions of the boreholes, hampers a subdivision of the Quaternary basin fill into hydro-stratigraphic units. Most of the reports on the groundwater setting in the coastal lowlands of north Java, drafted by various national and foreign consultants, mention repeated failure to correlate well logs. They all stress this specific aspect of the Quaternary sediments, i.e. the intangible hydro-stratigraphy as deduced both from drilling samples and examination of existing wells. On the other hand, well depth information gathered from systematic surveys of the abundant deep tube wells in the coastal lowlands does suggest a sequence of water-transmitting layers alternating with less pervious strata.

It should be obvious at this point that the recognition of a hydro-stratigraphic subdivision in the Quaternary deposits underlying the present-day coastal lowlands is bound to fail by using the classical techniques of lithological similarity between adjacent boreholes. In this study two different approaches are followed:

1) Deduction of the historical sedimentary filling of the Quaternary basins, based on knowledge gained in the Tertiary hinterland, with respect to the major Pleistocene geological and climatological events. Pronounced geological events have taken place in the provenance areas of the Quaternary basins and conceivably must have impressed their characteristics on the accumulating sediments. The significance of the Pleistocene climatic fluctuations and major volcanic and tectonic events is evaluated to predict sedimentation in the basins; in particular the type of sediments, expected depositional environments, chronology and relative rate of basin filling.
2) The availability of abundant tube well data, collected during extensive field surveys in the six kabupatens, allow statistical treatment which may reveal horizons favourable for groundwater abstraction.

These approaches will be elaborated further in the following chapters.

5.2 *Sedimentation in the Quaternary basins*

The Pleistocene emergence of the island of Java, as described in the previous chapter, was accomplished both by uplifts from rising magma bodies and build-up of volcanic cones. In this way vast areas came under the influence of degradational processes and ETA systems were triggered causing accumulation of eroded materials both on the southern side of Java in the fore-arc basin and the major part of the sediment load presumably on the northern side over the late Pliocene coastal plain deposits.

As evidenced by the reported thickness of 200 to 300 m for the Quaternary sediment pile in the Jakarta area and in other parts in the study area of at least 150 m, it follows that sedimentary basin formation has taken place during the Pleistocene epoch. Subsidence of the sedimentary basins may have originated by a combination of consolidation of the underlying Tertiary clayey deposits and isostatic movements. Le Pichon et al. (1976) pointed out that the zone 200 to 300 km from the trench axis subside progressively through time, whereas the 100 to 150 km zone is progressively uplifted. The hinterland of the present-day coastal lowlands exhibit E-W regional marginal faults or flexures which are well developed along the stretch Semarang to Cirebon, reappear in the southern part of kabupaten Indramayu and can also be traced further to the west.

As seen from a plate-tectonic setting, the Quaternary sedimentary basins can be classified as being of a 'marginal back-arc' type. A tectonic mechanism can be invoked which consisted of the rising effect of the Java geanticline compensated volumetrically by subsidence in the marginal aligned trough. If it is assumed that basin creation is indirectly controlled by these plate-tectonic mechanisms, then a tectonic hinge zone can be expected to exist connecting the rising and subsiding geo-realms. This hinge zone, its tectonics and structural appearance along the southern margin of the coastal lowlands, was described at length in Chapter 4. For both mechanisms of marginal basin formation (simple isostatic subsidence or basin formation beyond a tectonic hinge zone) one may expect the thickness of sedimentary fill to decrease with distance from the longitudinal axis. Thus the thickness of the Quaternary sediment pile is likely to be reducing in a northerly direction beneath the present-day Java sea.

Table 5.1 Quaternary basin history and major geological events.

EPOCH	AGE	EXPECTED DEVELOPMENTS AND DEPOSITIONAL CONDITIONS IN THE QUATERNARY BASINS NORTH OF THE HINGE ZONE	Major geologic events
HOLOCENE		Outward building northern coastal lowland deposits marine clay blankets, delta deposits, floodplain clays	Starting cone collapses and foot folding
HOLOCENE / PLEISTOCENE	UPPER	Influx of volc. materials; volc. fan building and frequently shifting stream channels. Cycles of savanna-like environments with sheet-flood deposits of coarser materials and volc. fans during dry periods, overlain by marine clays and coastal swamp deposits in turn overlain by floodplain clays. Deformation of the southern flanks of the basins by northward directed thrust movements and diapiric movements of underlying Tertiary rocks.	Regional reactivated volcanism along existing vents Uplifting
PLEISTOCENE	UPPER		Local collapses of cones warping and folding of cone feet
PLEISTOCENE	MIDDLE	Unstable depositional environments. Large supply of volcanic materials during the 'old volcanic' cycle as airborne ashes and reworked tephra. The bulk of the sediment pile originated presumably from this period onwards. Widepread transgressions during interglacials. Widely shifting coastlines, locally variable, due to rapid transgressions and by delta building.	Regional piercing of magmas with widespread volcanism
PLEISTOCENE	MIDDLE	Reactivation of the major transverse faults and subdivision of Java into structural sectors. Increasing instabilities of the depositional environment. Increasing contrast between basin filling in West and Central Java. Cyclic sedimentation due to wet and dry periods with many unconformities. Floodplain and marine clays during wet climates and fans with coarse materials during dry periods.	Transverse faults; Regional collapse along deep-seated E-W faults; formation of Bandung/Garut basins;
PLEISTOCENE	LOWER	Relatively stable environment, alternation of wet and dry periods. Fluctuating sea levels. Minor marine strata (?). Influx of volc. sediments in Central Java, Tertiary erosion products in West Java. Vast coastal lowlands with initiation of uplifts along the Java geanticline. Sediments mainly erosion products from fine-grained Tertiary rocks Influx of erosion products from Sunda craton (?)	Regional uplifts by ascending magmas Local volcanism Northward glidings and thrusts
PLIO		Coastal lowland settings with fluvial, deltaic and shallow marine deposits, abrupt facies changes	Uplifting

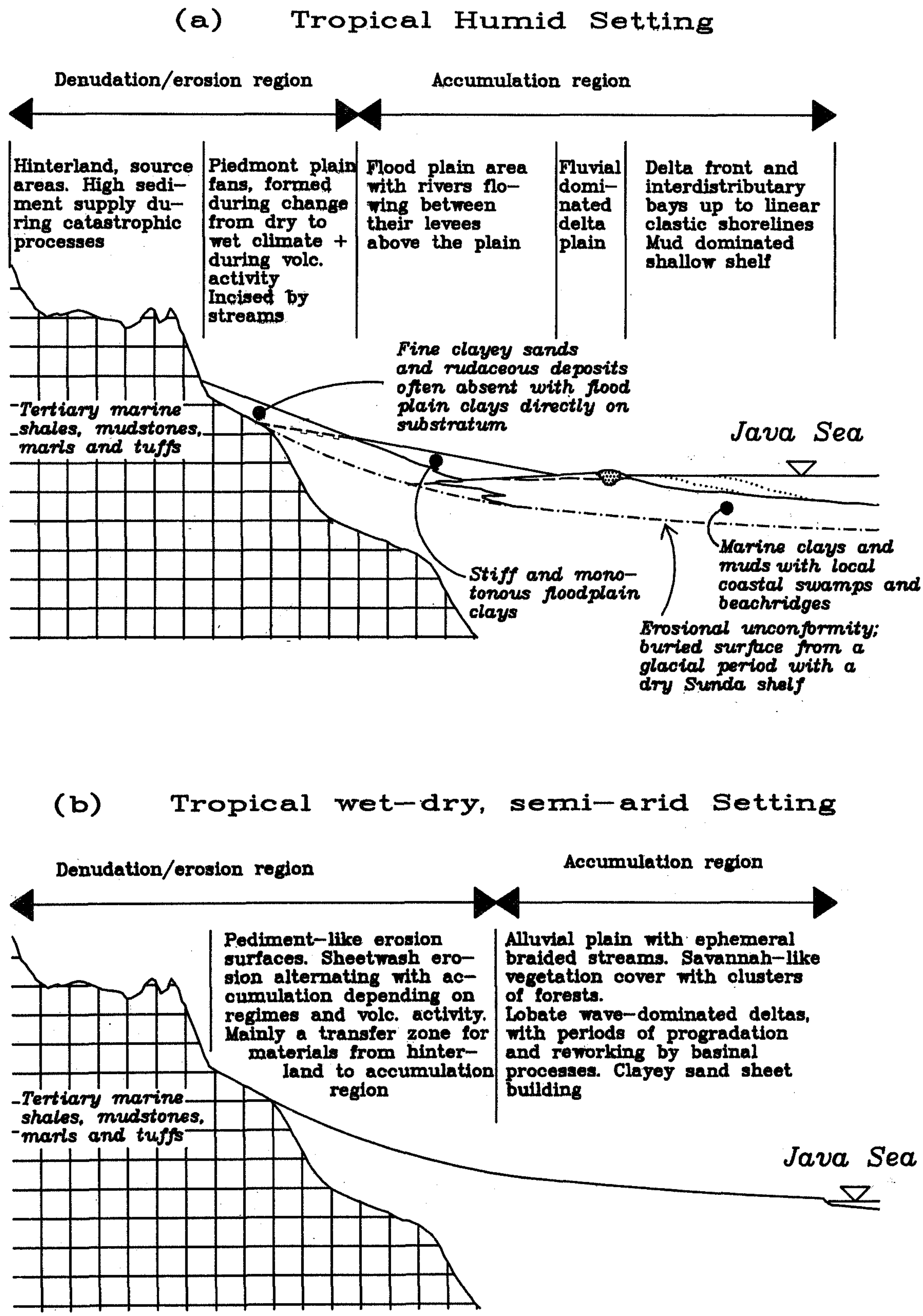


Fig. 5.1 General sedimentation model for the coastal lowlands.

At this stage it is worthwhile to contemplate the major geological events that occurred during the Pleistocene epoch, as enumerated in Table 5.1, and the significance of these regional events both upon the depositional environment in the basins and conditions in the source areas. Although these events are not sufficient to fully reconstruct the sedimentary basin history, general trends can still be recognized.

At the outset of the Pleistocene epoch a vast coastal lowland existed underlain by the Upper Pliocene formations such as Kaliglagah, Citalang, Ciherang, Citulang and Lower Damar. The hinterland may have consisted of a low relief hilly topography with some local volcanism. Local volcanism continued in the Lower Pleistocene, especially in the Central Java sector, and regional uplift movements became noticeable in the West Java sector. As a result of these events in the hinterland the ETA systems gained in importance and the accumulation of clayey coastal lowland and marine sediments probably increased with locally more input from reworked volcanic deposits. One may even speculate on the input of erosion products from the supposed land area of crystalline rocks of the Sunda craton exposed in the middle of the Java Sea, during the Lower Pleistocene. However, the difference in accumulation of sediments in the Lower Pleistocene as compared to the Upper Pliocene may not have been too dramatic.

As regional uplifts progressed in the Lower Pleistocene, presumably accompanied by hinge faulting, the sediment supply from the uplifted Tertiary hinterland may have increased also. Superimposed on this effect of increasing sediment supply, the Pleistocene climatic fluctuations must have had their impact on sediment supply.

Glacials on the northern hemisphere provoking tropical wet-dry or even semi-arid conditions in these regions may have resulted in an extra supply of sediments. Together with lowerings of the sea level during the early Pleistocene glacials, it can thus be argued that the initial filling of the basins during the Lower Pleistocene occurred mainly in a continental setting. Afterwards, in the Lower Pleistocene, a normal cycle of rapid transgressions and regressions can be expected synchronized with the major climatic fluctuations.

The most important geological event is the regional piercing of magmas in the Middle Pleistocene causing widespread volcanism. This event must have changed the sediment supply dramatically and the major part of the marginal basins have been filled from this event onwards. The rising magmas and ascending batholiths at deeper levels may have increased the subsidence rates in the marginal basins. Since major deformation by cone collapse and warping took place after the building up of the old volcanic arc, it is reasonable to expect that strata in the marginal basins are also affected, as shown in the geological cross sections of Fig. 4.5. It implies that major tectonic elements such as the peculiar radial faults, thrust faults and asymmetric folding may run into the basins. Since volcano collapse by gravity forces is not an instantaneous process, even on a geological time scale, warping and diapiric squeezing of the soft underlying claystones may have seriously affected the southern flank of the basins.

In Table 5.1 a summary is given of the assumed conditions in the Quaternary basins. The sedimentary basin history in the Lower Pleistocene is difficult to reconstruct, but the major build-up of the sediment pile may have taken place predominantly after the widespread old volcanism. A typical characteristic is the cyclic sedimentation due to fluctuations in sea level. Continental settings from glacials, if not counterbalanced by terrestrial sedimentation, are rapidly submerged by interglacial transgressions of up to 1 m/100 years (Chorley et al., 1984, Lowe & Walker, 1984) resulting in the covering of relict sediments by marine clays. Reading (1982) mentions maximum sea level rises of 2.4 m/100 years. Consequently, a period of rapid transgression is followed by outward coastal building in which the marine and near-shore deposits become overlain by floodplain clays.

A general sedimentation model for the coastal lowlands is presented in Fig. 5.1. A tropical humid setting as at present, reveals a well defined incised piedmont plain, a vast flood plain area and a prograding delta plain which becomes gradually overlain by the flood plain clays. Offshore, a mud dominated shelf is found. In a drier climate setting, flashy regimes may result in a shifting boundary between the denudational and accumulation areas. In this setting it is postulated that coarse materials are much easier spread over the accumulation areas than in a humid setting with predominantly suspended loads.

5.3 Depth distributions of water wells in the coastal lowlands

5.3.1 Introduction

The most striking feature of the northern coastal lowlands of Java is the problematic state of domestic water supply from groundwater resources. Strongly varying water qualities are found in a vertical and horizontal sense, mostly unfit for human consumption. Extensive parts of the coastal lowlands contain saline shallow groundwater resources which may be used for washing and bathing purposes only. In order to alleviate the domestic water supply problem, deep water wells were already sunk at the beginning of this century. Most of these large-diameter, originally self-flowing deep wells are still producing groundwater, albeit nowadays by hand-pump.

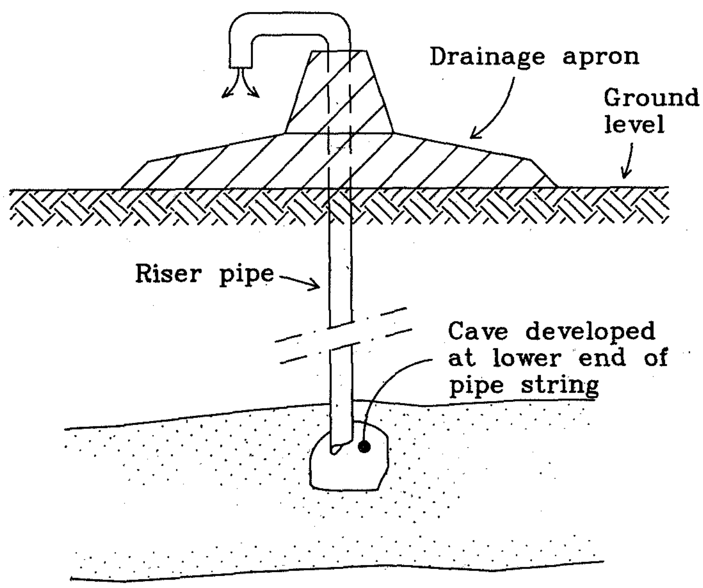


Fig. 5.2 General construction of small diameter tube wells as found in the coastal lowlands.

Numerous deep tube wells have been drilled in the last two decades to meet water demands of the rapidly increasing population in the coastal lowlands (see Fig. 5.2). Tube wells consist mostly of pipe strings (galvanized steel pipe with standard lengths of 6 m or even polyvinyl chloride pipes with 4 m standard lengths for domestic water supply) with nominal diameters of 25 to 50 mm, drilled by jetting methods and hand power. Pipe connections are made by plain threaded fittings. The low-technology drilling method, requiring a general purpose small motor-driven pump and a tripod, is well suited for rural areas and can be mastered easily by the local population. In general, sinking of tube wells is carried out by informal local drilling contractors. The lower end of the pipe string is obliquely cut by a hacksaw or a chisel-shaped bit is attached by welding, acting as the drilling bit. By rotating the pipes by hand and pumping water into the upper end of the pipe string depths of more than 100 m are easily obtained. Upon reaching a water-transmitting layer, preferably under artesian pressure, drilling activities are terminated and a hand-pump may be temporarily installed to develop the well. Screens are absent and groundwater enters the well at the lower end of the pipe string. Developing the tube well is necessary in order to create a cave at the lower end which acts as a sand trap. These tube wells can be self-flowing or may require the installation of a hand-pump. Finishing the tube well consists of pouring a concrete block and a drainage apron.

The advantage from a hydrological point of view is that groundwater is withdrawn only at the lower end of the pipe. Local tube well owners nearly always recall exactly the number of 'pipe lengths' which were sunk into the ground. Besides these tube wells, the traditional dug well with a brick lining remains popular in areas with fresh shallow groundwater. However, even in these areas, depending on the aquifer materials, the much cheaper shallow tube wells of 6 to 12 m depth equipped with a hand-pump are becoming popular. Water wells drilled under Indonesian development programmes consist mainly of large diameter wells (150 to 200 mm) with gravel-packed screens.

5.3.2 *Collected water well data*

During systematic groundwater investigations in all six kabupatens, a total of 3357 wells have been surveyed and filed in a digital database (see Fig. 5.3). Surveys were carried out from 1981 to 1984 in four West Java kabupatens in the framework of the Indonesian-Dutch development project OTA-33, in an effort to compile groundwater availability maps on kabupaten scale. In 1986 survey activities were continued in two neighbouring kabupatens in Central Java as part of the cooperation between the Gadjah Mada University and the Free University, Amsterdam. The surveys have been conducted largely by the present author, by teams of Indonesian and Dutch university students and Indonesian technician level surveyors. Table 5.2 shows more details of the number and type of surveyed wells in each kabupaten. Collected well data comprise normal parameters such as total depth, electrical conductivity of the well water, water temperature and local verbal information on discharge variation, water table fluctuations and dry season performance. Water samples have been collected from 659 wells for chemical analyses.

Information from local inhabitants relating to the depth of the pre-war deep wells is doubtful. However, much information on these old wells could be recovered from descriptions in the 'Jaarboek van het Mijnwezen' and archives at the Directorate of Environmental Geology in Bandung. Since, tube wells provide the most useful hydrological information on specific depths of water-transmitting layers and the chemical quality of groundwater at those depths, most statistical analyses are confined to these wells.

Table 5.2 Collected well data showing the numbers of wells by type and kabupaten.

Kabupatens	Artesian tube wells	Pumped tube wells	Pre-war wells	Dug wells	Totals
Brebes	47	277	3	572	899
Cirebon	20	242	7	138	407
Indramayu	76	134	22	353	585
Karawang	101	63	18	65	247
Subang	157	263	2	117	539
Tegal	29	175	2	474	680
Totals	430	1,154	54	1,719	3,357

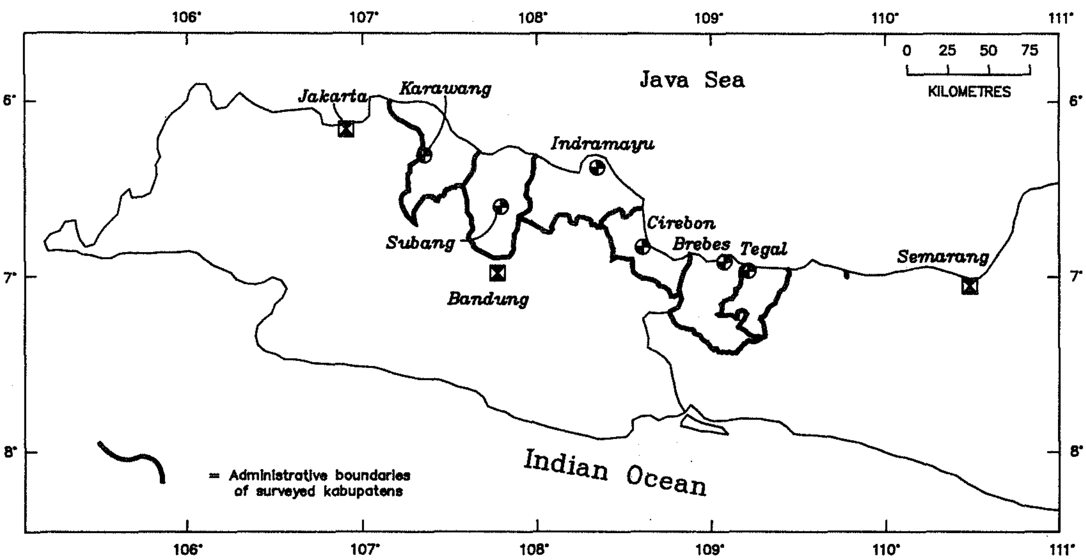


Fig. 5.3 Location of the six studied kabupatens.

5.3.3 *Statistical analyses of tube wells depths*

Viewed against the background of geological developments which have taken place since the end of the Pliocene, it is untenable to assume a homogeneous lithology of the sediments in the basins. The profound climatic changes throughout the Pleistocene even in this part of the Indonesian archipelago (Williams in Douglas & Spencer, 1985) as pointed out in preceding Chapter 4 and the obvious periods with increased volcanic activity must have had direct effects on the sediment provenance areas and depositional conditions in the basins. The following hypotheses can thus be advanced:

1) a regionally consistent layering is present in the sediment pile of the Quaternary basins;
2) tube wells will mainly penetrate the Quaternary sediments until regional horizons are met which contain coarser materials;
3) a population of tube wells tapping groundwater from a regional water-transmitting layer will give rise to a cluster in a depth frequency diagram. The cluster will approach a Gaussian probability distribution.

The histogram in Fig. 5.4 shows the frequency distribution for depth of the entire surveyed population of tube wells, both artesian and pumped. The class interval is based on standard pipe lengths of 6 m.

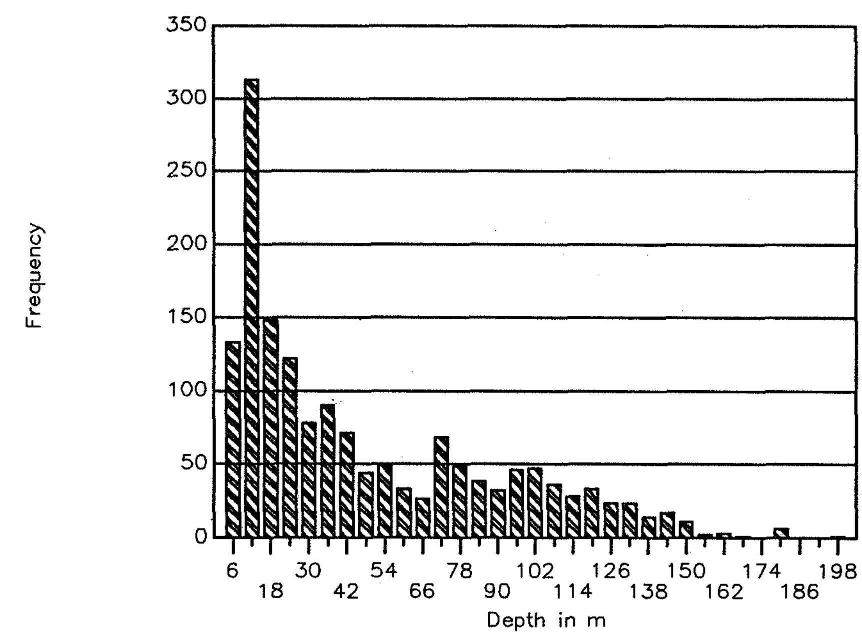


Fig. 5.4 Depth-frequency distribution for all tube wells (artesian + pumped, N = 1,584).

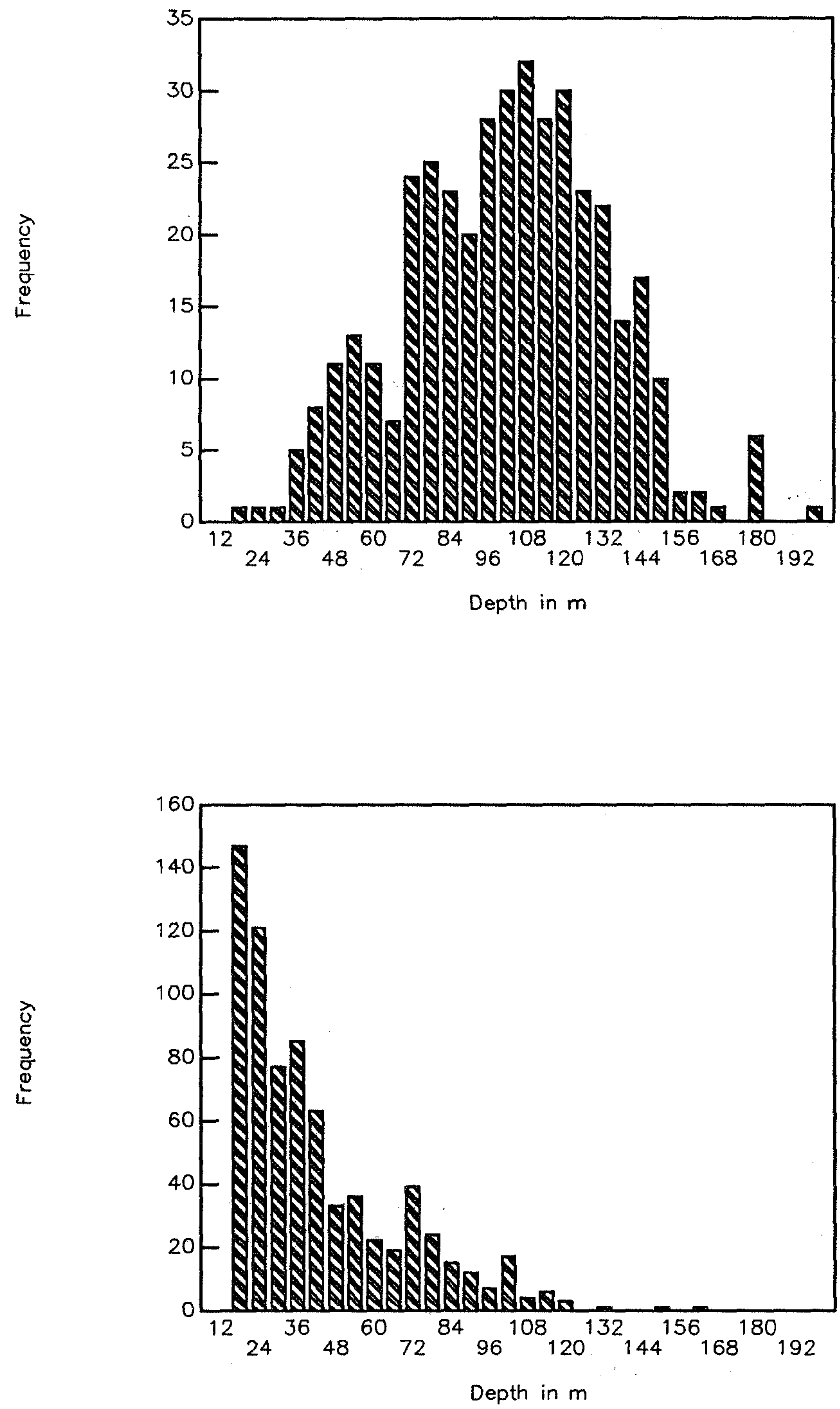


Fig. 5.5ab **Depth-frequency distributions for (a) all artesian with depth > 12 m (N=405, upper diagram) and (b) all hand-pumped tube wells with depth > 12 m (N=733, lower diagram).**

Most of the wells tap groundwater from shallow depths; the median is found at a depth of 33 m. Since artesian and pumped tube wells are combined in this histogram it is difficult to recognize the depth zones with artesian conditions. The relatively large number of shallow tube wells may result in a distorted impression of the histogram, hence a lower limit of 12 m is used in Fig. 5.5 depicting separately all artesian and hand-pumped tube wells. A glance at the entire population of artesian tube wells (Fig. 5.5a) gives the impression of a trimodal frequency distribution. The depth distribution of artesian tube wells is by far the most attractive to analyse statistically, because artesian tube wells specifically reflect hydrological conditions and exclude unwanted side effects.

The number of artesian tube wells displayed in Fig. 5.5a is only 405, due to the omission of wells with doubtful depth information. As estimated visually, the first peak is found at a depth of about 54 m, a second less pronounced peak at roughly 78 m and a third peak at 108 m. Despite distortion of the histogram by the shallow hand-pumped tube wells, similar peaks can be vaguely recognized in Fig. 5.5b.

Tube wells tapping a regionally consistent non-dipping water-transmitting layer, with randomly distributed thin sheet sands and having a total theoretical thickness which is much smaller than the depth of burial, are expected to show depth-frequency distributions which approximate Gaussian density distributions. Irrespective of the theoretical distribution, the mean and variance are finite in this model. The central limit theory states that the means of random samples of fixed size drawn from a population whose theoretical distribution is of an arbitrary shape but with a finite mean and variance, will tend to be increasingly normally distributed as the sample size increases. Furthermore, the depth variable is continuous, the consecutive values are independent and the probabilities are stable.

If the hypothesis of surmised regionally consistent layering holds for the Quaternary sediment pile, then the probability distribution of the entire population of artesian tube wells will consist of a mixture of approximately Gaussian components. Mixed frequency distributions are well known in the fields of biometrics (Bhattacharya, 1967, Dick & Bowden, 1973) and geology (Clark, 1976, Koch & Link, 1980). However, analysis of mixed distributions and decomposition into component distributions and respective proportions is a long-standing problem. Methods of moments and maximum likelihood and graphical methods using normal probability paper have been applied by various researchers for mixtures of two components. The difficulties of decomposition increase tremendously as the number of components increase or are not adequately separated.

Three methods are applied in an attempt to decompose the depth-frequency distribution for all artesian tube wells into its basic Gaussian components. The first is a semi-graphical procedure, the second is based on cluster analysis and finally a non-linear least-squares method is presented.

A Gaussian probability function P(x) has the useful characteristic of rendering a straight line when plotting $\mathrm{Log}_e(P(x+h))-\mathrm{Log}_e(P(x))$ versus x, where h represents a constant interval. This can be derived as follows:

$$P(x) = \frac{1}{\sigma\sqrt{(2\pi)}} e^{-(x-\mu)^2/2\sigma^2} \qquad (5.1)$$

P(x) = Gaussian probability density function

μ = population mean
σ = population standard deviation

$$\mathrm{Log_e}(P(x+h)) = \mathrm{Log_e}\{\frac{1}{\sigma\surd(2\pi)}\} - (x+h-\mu)^2/2\sigma^2 \tag{5.2}$$

$$\mathrm{Log_e}(P(x)) = \mathrm{Log_e}\{\frac{1}{\sigma\surd(2\pi)}\} - (x-\mu)^2/2\sigma^2 \tag{5.3}$$

if $p = x-\mu$, then:

$$\mathrm{Log_e}(P(x+h)) - \mathrm{Log_e}(P(x)) = \frac{p^2 - (p+h)^2}{2\sigma^2} \tag{5.4}$$

$$= \frac{-2h(x-\mu) - h^2}{2\sigma^2} \tag{5.5}$$

It follows that equation 5.5 is linear in x, thus the left hand term will plot as a straight line versus x. At points where $\mathrm{Log_e}(P(x+h))-\mathrm{Log_e}(P(x))$ attains a value of zero, the mean μ can be derived. Thus equation 5.5 becomes:

$$\frac{-2h(x-\mu) - h^2}{2\sigma^2} = 0 \tag{5.6}$$

$$\mu = x + h/2 \tag{5.7}$$

In Fig. 5.6a, $\mathrm{Log_e}(P(x+h))-\mathrm{Log_e}(P(x))$ is plotted versus x for all artesian tube wells. The straight line near the X value of about 53 m corresponds well with the first peak of Fig. 5.5a. The second less pronounced peak around 78 m emerges also in Fig. 5.6. The remaining part of the graph remains obscure, due to the differing frequencies in this part of the histogram and nothing can be said about the third peak around 108 m. A similar graph is displayed in Fig. 5.6b for the entire population of tube wells. In this graph two straight section can be drawn, one near 36 m and a deeper one at about 100 m.

Cluster analysis has been applied to the depth distribution of artesian tube wells. Convenient procedures like 'Quick Cluster' from the SPSS statistics package assign cases to the nearest cluster centre, which can be specified or calculated from the data. Table 5.3 shows the results of this procedure, which is based on Euclidean distances between the cluster centres and each case. It uses the depth data as input and the number of requested clusters must be specified; thus 3 clusters in each of the runs 1 and 2 and finally 2 clusters in run 3 of Table 5.3. The first cluster centroid at 54 m depth is also recognized by the procedure, but the two remaining centroids are calculated at greater depths.

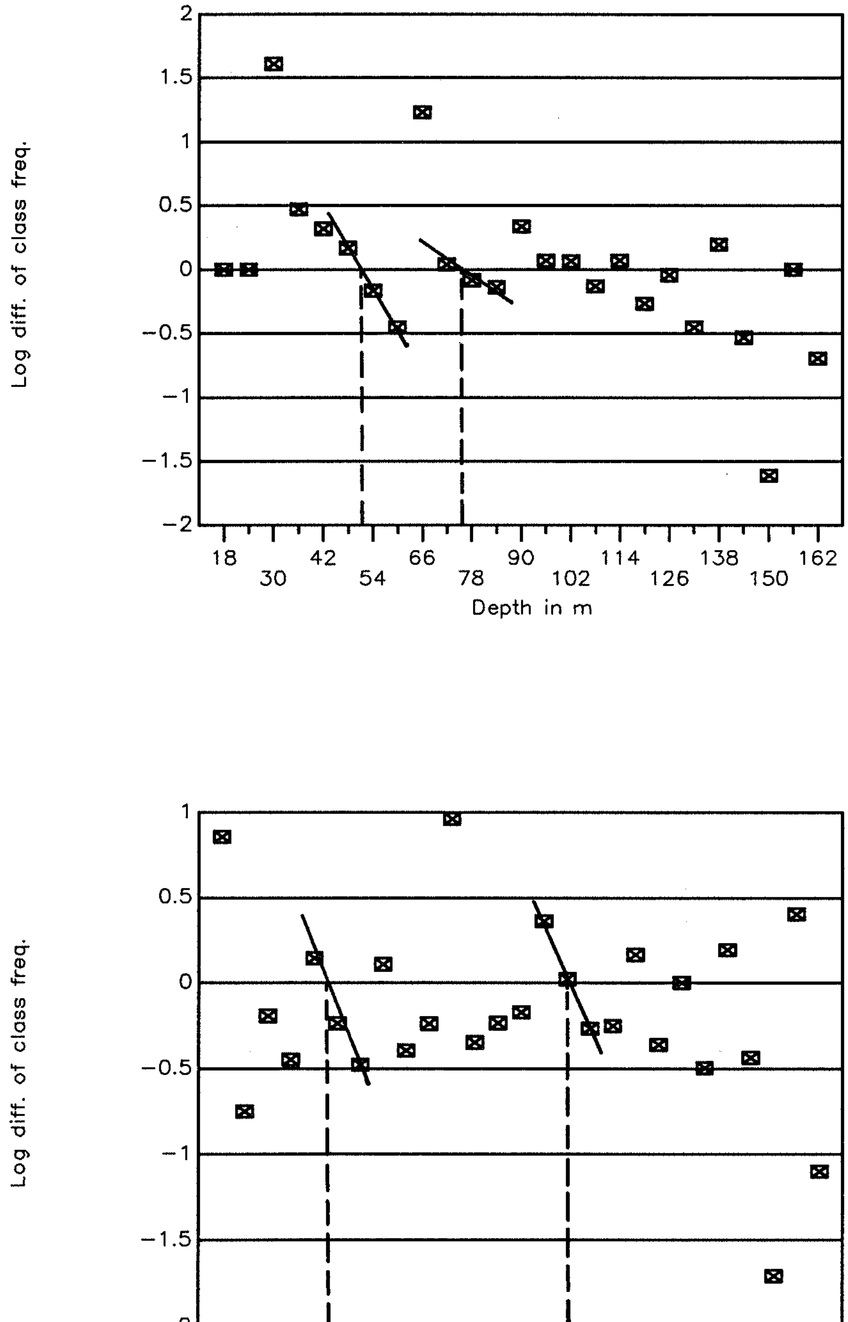


Fig. 5.6ab Log differences of class frequencies versus depth for (a) all artesian tube wells (N=405, upper diagram) and (b) the entire tube well population (N=1584, lower diagram).

The difference between a run with specified initial cluster centroids and one in which a number of three clusters is requested results in a shift of about 4 m. Requesting for two clusters results in a lumping of the first two clusters, which is unlikely when the pronounced relative minimum between both clusters is considered. Hence, the two-cluster model is disregarded for further analysis.

Table 5.3 Cluster analysis on artesian tube well depth data with cluster centroid results in m depth.

Run	Initial Clusters			Final Clusters		
1	54	78	108	51	91	132
2	Not specified, 3 clusters requested			48	87	128
3	Not specified, 2 clusters requested				74	124

The same procedure applied to depth data for all tube wells, both artesian and pumped, and also to only pumped tube wells is strongly influenced by the skewed distribution with the median at 33 m and mean at 48 m.

Table 5.4 Final cluster centroids for all tube well data and pumped tube wells, with depth of centroids in m.

All tube wells			Pumped tube wells		
N = 1,584			N = 733		
18	71	122	27	68	108
Depth > 24 m					
N = 868			N = 465		
41	84	128	39	75	111

Table 5.4 shows the results for 3 requested clusters both for the complete set of depth data and for selected data with depths greater than 24 m. The number of tube wells is strongly reduced by selecting depths of more than 24 m and the final clusters approach those found for the artesian tube wells in Table 5.3. The abundance of shallow pumped tube wells apparently masks the first peak in the depth distribution of all artesian wells at about 50 m.

The third method applied to the artesian tube well depth data in order to resolve the surmised Gaussian components is non-linear least squares regression. The model to be fitted by non-linear regression consists of a summation of m Gaussian components:

$$F(x;\alpha_i,\mu_i,\sigma_i) = \sum_{i=1}^{m} \frac{\alpha_i}{\sigma_i\sqrt{(2\pi)}} e^{-(x-\mu_i)^2/2\sigma_i^2} \tag{5.8}$$

α_i = proportion factor

For each component three parameters must be estimated: the mean, variance and proportion. More precisely, a total of i (i = 3m-1) unknown parameters have to be solved.

The objective is to fit an observed series of data points y_j (j=1 to n) to predicted values by expression 5.8. The least squares method is based on minimizing the squares of residuals r_j, i.e. the difference between observed and predicted values. Thus the following function, with the unknown parameters must be minimized:

$$R(x) = \sum_{j=1}^{n} (y_j - F(x;\alpha_i,\mu_i,\sigma_i))^2 \tag{5.9}$$

or:

$$R(x) = \sum_{j=1}^{n} r_j^2(x) \tag{5.10}$$

Scales (1985) gives the derivatives of sum-of-squares functions, leading to least squares normal equations to be solved for the unknown parameters. A direct solution in a non-linear situation is not possible and therefore an iterative method must be used. An appropriate numerical algorithm is the Gauss-Newton method. This method belongs to the small residual algorithms, in which terms with higher derivatives are ignored, and Scales (1985) proposes the following matrix notation for the basic iteration:

$$J_n^T . J_n . p_{n(k)} = -J_n^T . f_{n(k)} \tag{5.11}$$

$$x_{n(k+1)} = x_{n(k)} + p_{n(k)}$$

J_n^T = Transposed Jacobian matrix of order n
J_n = Jacobian matrix of order n
$x_{n(k)}$ = vector of n parameters at iteration cycle k
$p_{n(k)}$ = search vector of order n at iteration cycle k
$x_{n(k+1)}$ = new estimated vector of n parameters
$f_{n(k)}$ = vector with function values evaluated at cycle k
n = number of parameters to be estimated.

In this study a non-linear least squares routine is adopted from Clark (1977), based on the Gauss-Newton method. Input consists of frequencies in the fixed depth intervals such as shown in Fig. 5.5a and initial estimates of the parameters and number of Gaussian components.

Table 5.5 Results of non-linear least squares fitting of three Gaussian components to the depth data for all artesian tube wells.

ORIGINAL DEPTH DATA, Normal components				
	Component	Mean	St. Deviation	Percentage
Initial estimates	1 2 3	48 87 128	5 5 20	20 30 50
Initial Chi-squared goodness of fit = 655.9 (12 deg. freedom)				
Final estimates	1 2 3	48.4 84.9 116.7	11.0 16.3 22.1	13.4 32.1 54.5
Final Chi-squared goodness of fit = 26.8 (13 deg. freedom)				

ORIGINAL DEPTH DATA, Lognormal components				
	Component	Mean	St. Deviation	Percentage
Initial estimates	1 2 3	48 87 128	5 5 20	20 30 50
Initial Chi-squared goodness of fit = 789.7 (12 deg. freedom)				
Final estimates	1 2 3	71.3 104.8 129.6	30.8 23.7 11.4	28.6 61.5 9.9
Final Chi-squared goodness of fit = 25.5 (14 deg. freedom)				

SMOOTHED DEPTH DATA BY 6th. ORDER POLYNOMIAL, Normal components				
	Component	Mean	St. Deviation	Percentage
Initial estimates	1 2 3	48 87 128	5 5 20	20 30 50
Initial Chi-squared goodness of fit = 695.5 (12 deg. freedom)				
Final estimates	1 2 3	57.6 85.5 119.3	16.2 15.6 20.4	19.3 29.5 51.2
Final Chi-squared goodness of fit = 1.13 (13 deg. freedom)				

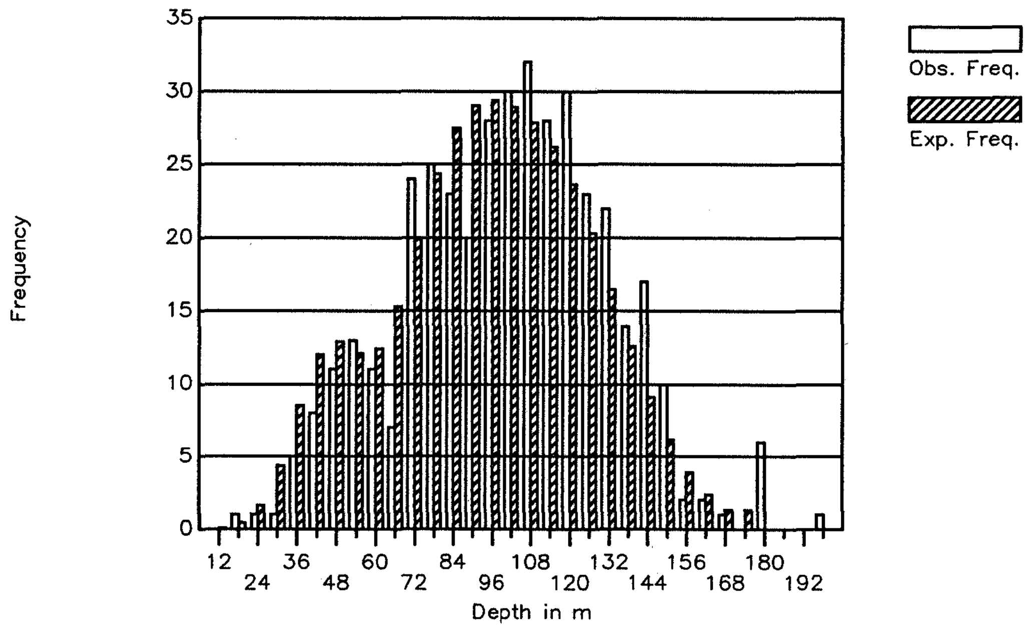


Fig. 5.7 Observed and expected frequencies of artesian tube well depths (depth > 12 m, N=405).

Fitting of three normal and log-normal components is applied to the original depth data and to data which is first smoothed by fitting a 6th order polynomial. The class interval of 6 m is also maintained in this least squares analysis. Despite the stepped frequency curve and irregular parts in the histogram of Fig. 5.5a, subdividing the classes will render the histogram unwieldy and data compression into too few classes obscures the details. Table 5.5 shows the results of least squares regression. Initial estimates are given based on the component peak centres as found by previous methods.

The first analysis of fitting three normal components to the original depth data yields parameters, except for the deepest component, which agree very well with results from the cluster and graphical procedures. Although the least squares analysis was repeated many times with different starting values, the lowest Chi-squared goodness of fit statistic which could be attained for unsmoothed data was only 26.8 with 13 degrees of freedom. The critical value at the 0.95 significance level, however, is 22.4 for 13 degrees of freedom. Undoubtedly, the relatively high Chi-squared value must be attributed to the stepped frequency curve, hampering a good fit (see Fig. 5.7). In the second analysis, three log-normal components are fitted to the original data and show a similar Chi-squared goodness of fit statistic. The critical value for 14 degrees freedom is 23.7, which is again exceeded by the calculated value. The estimated parameters of the three log-normal components deviate considerably from the previously determined means and standard deviations. The first two components with mean depths of 71 and 104 m are rather absurdly, as are the relative proportions. Based on these results, the fitting of log-normal components is disregarded for further analysis. The third analysis is applied to the same depth data, though in this case first smoothed by a 6^{th} order polynomial. The Chi-squared value which reduces from 695.5 (12 D.F.) to 1.13 (13 D.F.) reflects the good fit using three normal components. Apart from the slightly deeper depth for the first component, the remaining parameters correspond very well with the first analysis. Results of the fitting analysis are graphically displayed in Fig. 5.7 for the first procedure using original depth data fitted to a Gaussian three component model.

The next step is to classify the artesian tube well depth data into one of these three clusters, thus determining sampling boundaries.

Table 5.6 Descriptives of the three sampled clusters in the artesian tube well depth data, based on the results of Table 5.5.

Cluster	Cases	Mean	St.Dev.	Minimum	Maximum	95% conf. interval for mean	
1	58	49.8	11.1	15	64	46.9	52.7
2	137	84.3	9.5	69	99	82.7	85.9
3	210	124.2	18.6	102	193	121.7	126.7

The problem of classification, according to Hoel (1962), is a problem of dividing such a three-dimensional sample space in three parts S_1, S_2 and S_3 corresponding to the subpopulations. Based on the ratios of likelihood functions, laid down in the Neyman-Pearson lemma, Hoel (1962, p:363) proposes a theorem that yields the optimum decision boundaries, based on prior probabilities. Assuming Gaussian probability density functions $f_1(x)$ and $f_2(x)$ of the form of expression 5.1 with means μ_1, μ_2 and standard deviations σ_1, σ_2, the ratio becomes then:

$$\Lambda(x) = \frac{f_2(x)}{f_1(x)}$$

$$= \sigma_1/\sigma_2 \,.\, \exp[(x-\mu_1)^2/(2\sigma_1^2) - (x-\mu_2)^2/(2\sigma_2^2)] \qquad (5.12)$$

$\Lambda(x)$ = frequency function ratio
x = observed sample to be classified either to $f_1(x)$ or $f_2(x)$

The ratio is tested against the threshold value $A=p/(1-p)$ in which p represents the prior probability. This probability equals 0.5 to classify an observation x to belong to either $f_1(x)$ or $f_2(x)$. The decision limit is then defined by $\Lambda(x)=A$. Calculating the ratio by inserting the means and standard deviation of the Gaussian components as given in the first analysis in Table 5.5, results in a values of 65 and 102 m as the decision limits for depth cluster pairs 1-2 and 2-3, respectively. Table 5.6 shows statistical descriptives of artesian tube well data classified according to these decision limits. The means of the three population clusters found with non-linear least squares analysis, except for cluster 3, fall within the 95% confidence intervals for the sampled clusters. This is caused by omission of the overlapping tails between the clusters 2 and 3, hence the mean for cluster 3 in Table 5.6 is somewhat higher. The first cluster is well separated from the others, as evidenced by the sample standard deviation which approximates that found by least-squares regression. For the remaining clusters the sample standard deviation is smaller, due to overlapping tails.

Table 5.7 Results of the Kolmogorov-Smirnov test of normality on depth data for all artesian wells.

Sample	Cases	Mean	Standard deviation	K-S Z value	2-tailed probab.
Entire population	405	100.1	31.3	1.215	.104
Cluster 1	58	49.8	11.1	1.114	.167

The entire depth distribution of all artesian tube wells shown in Fig. 5.5a can be tested for whether it approaches a Gaussian probability distribution. An appropriate and sensitive test in this respect is the Kolmogorov-Smirnov one sample test given in the SPSS package. Table 5.7 lists the results of two tests on the artesian tube well data. Despite the low values for two-tailed probabilities, it is reasonable to assume a Gaussian distribution for the entire population. The cluster around 49 m is sampled according to the depth boundaries given by Table 5.6. This group when tested for normality also, shows a significant probability. Normality of the two remaining clusters is hard to prove because of poor separation and thus difficult grouping. Due to overlap, the tails remain unaccounted for in a normality test.

Table 5.8 Results of the Kolmogorov-Smirnov normality test on depth data for all artesian wells; clusters 2 and 3.

Sample	Cases	Mean	Standard deviation	K-S Z value	2-tailed probab.
Cluster 2 (original data)	137	84.3	9.5	1.965	.001
Cluster 3 (original data)	210	124.2	18.6	1.790	.003
Cluster 2 (generated data)	121	85.8	8.2	2.028	.001
Cluster 3 (generated data)	212	123.5	16.8	1.888	.002

Kolmogorov-Smirnov tests have been carried out on samples from both the original depth data and depth data as generated from the non-linear least-squares fitted results (see Table 5.5). The depth sampling boundaries for clusters 2 and 3 are taken from Table 5.6. The generated depth data represent the expected distribution with three Gaussian components, as given in Table 5.5. All tests failed to prove a normal distribution, which must be ascribed to poor separation which ignores the tails during sampling.

Table 5.9 One-Way analysis of variance on variable Depth by category variable Cluster for artesian tube well data.

Source	D.F.	Sum of squares	Mean squares	F ratio	F Prob.
Between clusters	2	303,076.91	151,538.46	663.97	0
Within clusters	402	91,748.23	228.23		
Total	404	394,825.15			

Although the differences in mean for the three clusters are quite evident from Table 5.6, a One-Way analysis of variance is performed to test the hypothesis that all the depth means for each cluster are equal and all the data are derived from the same population.

Table 5.10 One-Way analysis of variance on variable Depth by category variable Kabupaten for artesian tube well data.

Kabupaten	Cases	Mean	St. Dev.	95% conf. interval for mean
Brebes	42	86.5	31.7	76.9 - 96.1
Cirebon	20	76.7	38.3	59.9 - 93.5
Indramayu	69	88.4	34.8	80.2 - 96.6
Karawang	93	104.8	32.1	98.3 - 111.3
Subang	155	108.9	23.6	105.2 - 112.6
Tegal	26	101.5	28.7	90.5 - 112.5

	D.F.	Mean squares	F ratio	F Prob.
Between kabupatens	5	8,424.07	9.53	0.0
Within kabupatens	399	883.97		

In this analysis the variable Depth is considered as dependent and the category variable Cluster (from 1 to 3), also known as factor, as independent. The results are summarized in Table 5.9, showing that the null hypothesis, as expected can be rejected, implying unequal cluster means.

A more interesting application of One-Way analysis of variance is to test variations in the variable Depth by the category variable Kabupaten (from 1 to 6). This is to establish significant differences between depth observations in data sets for each kabupaten. The population of all tube wells for each kabupaten are compared for their homogeneity in variance and the results given in Table 5.10. The lower part of this table suggests that homogeneity does not exist between mean depths of the artesian tube wells when all data sets per kabupaten are used in the analysis. However, the means and standard deviations for the kabupatens Brebes, Cirebon and Indramayu on the one hand and Karawang, Subang and Tegal on the other, give the impression of conspicuous similarities. A One-Way analysis of variance is again performed on these two groups of kabupatens and a non-parametric Kruskal-Wallis test is used to test whether the k independent samples are from the same population. Table 5.11 shows significance levels for both tests which suggest homogeneity of mean depths for artesian tube wells in the two groups of three kabupatens.

Table 5.11 One-Way analysis of variance and Kruskal-Wallis tests, for artesian tube well data, on variable Depth by category variable Kabupaten (first group: Brebes, Cirebon, Indramayu and second group: Karawang, Subang, Tegal).

Brebes Cirebon Indramayu	D.F.	Mean squares	F ratio	F Prob.
Between kabupatens	2	1,077.53	0.91	0.40
Within kabupatens	128	1,185.84		
Kruskal-Wallis test		Cases	Chi-Sq.	Signif.
		131	3.44	0.18
Karawang Subang Tegal	**D.F.**	**Mean squares**	**F ratio**	**F Prob.**
Between kabupatens	2	882.45	1.19	0.31
Within kabupatens	271	741.39		
Kruskal-Wallis test		Cases	Chi-Sq.	Signif.
		274	3.63	0.16

The uniformity of mean and standard deviation is remarkable in each of the groups, particularly since the kabupatens have been independently surveyed by different students and field crews during separate field campaigns.

Table 5.12 One-Way analysis of variance, for artesian tube well data on variable Depth by category variable Kabupaten for the first depth cluster (variable Cluster preset at 1), Tegal is omitted.

Kabupaten	Cases	Mean	St. Dev.	95% conf. interval for mean	
Brebes	10	50.6	13.8	40.7 - 60.5	
Cirebon	11	51.8	10.5	44.8 - 58.9	
Indramayu	21	47.0	12.0	41.5 - 52.5	
Karawang	11	49.1	8.0	43.7 - 54.4	
Subang	5	57.6	5.4	50.9 - 64.3	
		D.F.	Mean squares	F ratio	F Prob.
Between kabupatens		4	131.36	1.08	0.38
Within kabupatens		53	121.81		
D.F. = 4		Median	Cases	Chi-Sq.	Signif.
Kruskal-Wallis			58	5.08	0.28
Median test		52.5	58	7.50	0.12

A last application of One-Way analysis of variance for artesian tube well data is the comparison of mean depths of wells among the six kabupatens for each of the three depth clusters. The Kruskal-Wallis and Median tests are also applied to the six independent cluster samples in order to compare the mean depths. Kabupaten Tegal is omitted from the analysis for the first cluster, due to the lack of artesian tube wells in this cluster. The levels of significance in the lower part of Table 5.12 indicate homogeneity of the depth means. Again remarkable is the small variation in standard deviation for the kabupatens Brebes, Cirebon and Indramayu.

Similar analyses for Cluster 2 in the artesian tube well depth data are summarized in Table 5.13. For these analyses kabupaten Cirebon is omitted because only four surveyed tube wells are found in this depth zone, giving a somewhat contrasting standard deviation and hence small F probabilities in the One-Way analysis of variance. Although the significance levels of the tests are lower than for Cluster 1, the analysis still suggests homogeneity of depth means. Finally, Table 5.14 compares the deepest clusters for all six kabupatens. Similar results are obtained showing homogeneous depth means for Cluster 3.

Table 5.13 One-Way analysis of variance, for artesian tube well data on variable Depth by category variable Kabupaten for the second depth cluster (variable Cluster preset at 2), Cirebon is omitted.

Kabupaten	Cases	Mean	St. Dev.	95% conf. interval for mean	
Brebes	22	81.3	7.7	77.9 - 84.7	
Indramayu	20	83.7	10.5	78.8 - 88.6	
Karawang	28	85.4	8.5	82.1 - 88.7	
Subang	49	87.0	9.5	84.3 - 89.7	
Tegal	14	81.8	10.2	75.9 - 87.7	
		D.F.	Mean squares	F ratio	F Prob.
Between kabupatens		4	168.47	1.97	0.10
Within kabupatens		128	85.47		
D.F. = 4		Median	Cases	Chi-Sq.	Signif.
Kruskal-Wallis			133	8.44	0.08
Median test		84.0	133	5.10	0.28

Although the result shown in Table 5.10 suggested differences in means for the group Brebes-Cirebon-Indramayu compared to group Karawang-Subang-Tegal for artesian tube well data, testing of homogeneity of means for each depth cluster in Table 5.12 to 5.14 does not reveal this feature. If the surmised inhomogeneity of means from Table 5.10 is caused by difference in sedimentary basin configuration, i.e. shallow mean depths in narrow coastal lowlands such as Cirebon and Brebes, one may expect this phenomena to emerge also in tests of mean homogeneity per depth cluster. Since the effect is absent a plausible explanation is the proportion of each of the three Gaussian components influencing the overall mean depth per kabupaten.

All the previous tests are applied to the population of artesian tube wells only, because of to the regular shape of the depth-frequency distribution. Nevertheless, One-Way and Two-Way analysis of variance can also be performed on the depth data sets of pumped tube wells and on the entire population of tube wells, by selecting wells deeper than a certain limit. Two-Way analysis of variance considers both variations within and among the data sets.

Table 5.14 One-Way analysis of variance, for artesian tube well data on variable Depth by category variable Kabupaten for the third depth cluster (variable Cluster preset at 3).

Kabupaten	Cases	Mean	St. Dev.	95% conf. interval for mean	
Brebes	10	133.9	16.7	122.0	145.8
Cirebon	5	135.6	25.3	104.2	167.0
Indramayu	28	122.9	16.9	116.4	129.5
Karawang	54	126.2	20.8	120.6	131.9
Subang	101	122.0	16.5	118.7	125.3
Tegal	12	124.5	25.9	108.0	141.0
		D.F.	Mean squares	F ratio	F Prob.
Between kabupatens		4	468.37	1.36	0.24
Within kabupatens		204	343.78		
D.F. = 4		Median	Cases	Chi-Sq.	Signif.
Kruskal-Wallis			210	6.46	0.26
Median test		120.0	210	2.85	0.72

The following outlines results of Two-Way analysis of variance (ANOVA), i.e. well depth by the factors Cluster and Kabupaten, for artesian and the entire population of tube wells. The objective of such a test is to determine whether homogeneity exists among the independent category variables Cluster (1 to 3) and Kabupaten (Karawang to Tegal), with Depth as the dependent variable. Table 5.15 shows that only the artesian tube well data give no significant differences between depth values for the six kabupatens when analysed in combination with the category variable or factor Cluster. It should be borne in mind that One-Way analysis of variance for the dependent variable Depth with the factor Kabupaten, as in Table 5.10, failed to prove equality of depth means among the six kabupatens. However, in Two-Way analysis of Depth by Cluster and by Kabupaten the value of F probability (0.83) indicates homogeneity among the kabupatens. This is logical because the source of greatest variation comes from the factor Cluster. In One-Way analysis the source of variation between data sets is considered to emanate from the factor Kabupaten only, which is fairly high. However, most of the variation is in fact caused by the factor Cluster. This is proved by the Two-Way analysis of variance, which indicates that 77% of the variance in the variable Depth can be explained by the factor Cluster.

Table 5.15 Summary of Two-Way analysis of variance (ANOVA) on variable Depth by the category variables Cluster and Kabupaten for artesian, pumped and all types of tube well depth data.

Tube well data	Cases	Source of Variation	D.F.	F Ratio	F Prob.	Explained variance
Artesian	404	Cluster	2	568.6	0.0	77%
		Kabupaten	5	.42	0.83	11%
Pumped depth > 24 m	464	Cluster	2	932.7	0.0	81%
		Kabupaten	5	6.94	0.0	6.7%
All types depth > 24 m	867	Cluster	2	2,359.9	0.0	86%
		Kabupaten	5	3.3	0.006	12%

ANOVA further reveals that the remaining source of variation caused by the category variable Kabupaten in this model is small, i.e. 11% of the variance in Depth can be explained by the factor Kabupaten. This discrepancy can be explained, since the factor Cluster determines the larger part of the variation and not the factor Kabupaten. In ANOVA this effect is recognized and the small variation caused by the factor Kabupaten results in a small value for F and thus a significant F probability. For the remaining well depth data sets, pumped tube wells and the entire population, it can be concluded that significant variations occur among the six kabupatens. The proportion of variance explained by the category variable Cluster is roughly the same and amounts to about 81% for the three data sets.

Based on these results of clustering and homogeneity of depth means, a summary is given in Table 5.16 of similar tests for the entire population of pumped and artesian tube wells and on the pumped tube wells only.

Table 5.16 Summary of One-Way analysis of variance on variable Depth by category variable Kabupaten for each cluster in pumped tube well depth data; depth > 24 m.

Cluster	Cases	D.F.	F Ratio	F Prob.	Kruskal-Wallis Prob.
1	335	5	12.12	0.0	0.0
2	98	5	1.79	0.12	0.06
3	32	4	4.89	0.004	0.01

Table 5.16 shows interesting results for the depth means of category variable Cluster in the six kabupatens. As can be expected for the depth interval of Cluster 1, no homogeneity exists among the depth means. Variations between the kabupatens are high and may be as-

sociated with varying local physical conditions and socio-economic factors. An observed tendency is noticeable that pumped tube well are used instead of an open dug well in order to improve socio-economic conditions. Homogeneity of depth means is suggested for Cluster 2, and can be explained in that former artesian tube wells now have to pumped. The sample mean and standard deviation of 78.8 and 8.0 m, respectively, approach the values for artesian tube wells in Cluster 2 listed in Table 5.6. The deepest Cluster 3 is apparently not the domain for pumped tube wells, as can be concluded from the rapidly decreasing number of cases in this depth zone.

Table 5.17 Summary of One-Way analysis of variance on variable Depth by category variables Kabupaten for each cluster in the entire population of tube well depth data; depth > 24 m.

Cluster	Cases	D.F.	F Ratio	F Prob.	Kruskal-Wallis Prob.
1	391	5	10.13	0.0	0.0
2	235	5	3.99	0.02	0.0
3	242	5	1.21	0.31	0.41

Likewise, this zone is not penetrated consistently on a regional scale and therefore homogeneity of mean depths is lacking. The failure to prove homogeneity of means for the depth zone of Cluster 1 is evident and reflects the variation of pumped tube wells in this zone. The One-Way analysis of variance on the artesian tube well depth data for Cluster 2 reveals (Table 5.13) low levels of significance, but still not sufficiently small to reject the null hypothesis. The combination of artesian and pumped tube wells, however, does not improve the level of significances for the depth zone of Cluster 2. The kabupatens Brebes and Cirebon in this respect are characterized by deviating mean depths.

Table 5.18 Summary of One-Way analysis of variance on variable Depth by the category variable Kabupaten on Cluster 2 for the entire population of tube well depth data; depth > 24 m and excluding kabupatens Brebes and Cirebon.

Cluster	Cases	D.F.	F Ratio	F Prob.	Kruskal-Wallis Prob.
2	176	5	0.62	0.60	0.49

A similar One-Way analysis of variance performed on the group of kabupatens, but excluding Brebes and Cirebon, again reveals the completely different statistical levels of significance shown in Table 5.18. Opposite results are shown for analysis of the two remaining kabupatens Brebes and Cirebon in Table 5.19.

Table 5.19 **Summary of One-Way analysis of variance on variable Depth by the category variable Kabupaten on Cluster 2 for the entire population of tube well depth data; depth > 24 m and for only kabupaten Brebes and Cirebon.**

Cluster	Cases	D.F.	F Ratio	F Prob.	Kruskal-Wallis Prob.
2	59	5	0.85	0.36	0.10

The results of the variance analyses shown in Tables 5.18 and 5.19 agree with the proposition that this depth zone of Cluster 2 represents a major domain for artesian tube wells and pumped tube wells which were once self-flowing. This points to regional consistencies of the depth zone, but limited to the kabupatens Brebes and Cirebon on the one hand and Indramayu, Karawang, Subang and Tegal on the other. The separation between Brebes, Cirebon and the other kabupatens such as Indramayu, Karawang and Subang seems plausible because of the location of the major groundwater basins. However, the position of kabupaten Tegal is not yet clear. Tegal is different in many aspects, as will become apparent later.

The F probabilities and Kruskal-Wallis test result for all tube wells in the depth zone of Cluster 3 all point to uniformity of mean depths. This is obvious, since the number of pumped tube wells is small compared with artesian tube wells in the zone. In fact the results of Table 5.14 are repeated, indicating that the depth zone of Cluster 3 is the major domain for artesian tube wells.

5.4 *Results and discussion*

The statistical exercises conducted in the previous sections were aimed at recognizing depth zones with a tube well tapping preference. It was hypothesized that it will be highly unlikely that the Quaternary sediment pile in the coastal lowland basins has a homogeneous stratigraphic and lithological record. However, a glance at the depth-frequency diagram for artesian tube wells in all six kabupatens reveals zones with definite concentrations of wells. It also appears that the population of artesian tube wells is the most appropriate data set to be subjected to statistical analysis. Artesian conditions, even when caused solely by aquifer compaction, implies a regional lateral dimension characterized by lateral physical homogeneities.

The statistical analyses performed in previous sections aimed to:

1) identify zones of depth concentrations for the whole population of artesian tube wells;
2) recognize lateral depth clusters among the various kabupatens.

The pumped tube wells and the complete population of tube wells are treated less rigorously by first applying corrections, with subsequent statistical tests aimed at demonstrating consistent lateral extension of depth concentrations.

The best method of decomposing the depth-frequency curve into Gaussian components appears to be by first applying simple cluster analysis and to continue with non-linear least squares regression to improve estimation of the parameters of the normal components. A reasonable fit is attained by assuming the depth-frequency diagram to consist of three normal components, with mean/standard deviation estimates: 48/11, 85/16 and 117/22. The proportions of the three components agree very well with the number of artesian tube wells in each of the clusters. Smoothing the original depth data by a 6th order polynomial improves the fit substantially. A log-normal distribution seems plausible for the clusters of artesian tube wells, since a skewed distribution of tube wells may be expected in the top of a regional transmitting layer. However, fitting of log-normal components resulted in unrealistic parameters.

Summarizing the statistical analyses applied to tube well depth data, it can be said that emphasis was laid on testing homogeneity of mean depths among the six studied kabupatens. Entering the entire population of tube wells in One-Way analysis of variance failed to prove equality of depth means. However, applying the same tests to the kabupaten groups Brebes-Cirebon-Indramayu and Karawang-Subang-Tegal, revealed sufficiently high probabilities to accept the null hypothesis. Comparison of mean depths among the kabupatens for each depth cluster, turned out to be more successful and homogeneity of means could be demonstrated for all clusters in the artesian tube well population, for the second depth cluster in pumped tube well data and for the deepest cluster in data of the entire tube well population. The regional lateral effect consistent layering is perhaps best reflected in the significant statistical probability levels from One-Way analysis of variance between kabupatens for depth zones belonging to one of the three depth clusters. The main conclusion is that the lower ends of the tube wells are found in three major depth zones which have lateral extensions into all studied kabupatens. Significant differences in mean depth of the zones among the kabupatens could not be established.

Table 5.20 Summary of One-Way analysis of variance on variable Depth by category variable Kabupaten for a group of artesian tube wells between two arbitrary boundaries of 40 and 91 m and a group of wells constituting a combination of Clusters 1 and 2.

Group	Cases	D.F.	F Ratio	F Prob.
40 to 91 m	143	5	4.9	0.00
Cluster 1+2	193	5	10.0	0.0

The statistical analyses performed so far do not reject the three hypotheses of the existence of depth clusters, the consistent regional extent of tube well depth zone preference and the Gaussian behaviour of the clusters. One could argue against decomposition into Gaussian components, in that the boundaries between components are fairly arbitrary and that a decomposition into two components may also hold. However, by choosing other arbitrary boundaries for the first depth cluster, with remaining data in the second cluster, One-Way analysis still fails to indicate homogeneity of depth means for the six kabupatens. Table 5.20 gives a summary of One-Way analysis on a group of artesian tube wells for six kabupatens within arbitrary boundaries of 40 and 91 m depth. Furthermore, a second test is applied to a combination of Clusters 1 and 2. The results are clear and the null hypothesis of equality of depth means for these groups outside the cluster boundaries can be rejected.

An interesting fact which emerged from the statistical analyses is the distribution of tube well types among the three clusters (see Fig. 5.8).

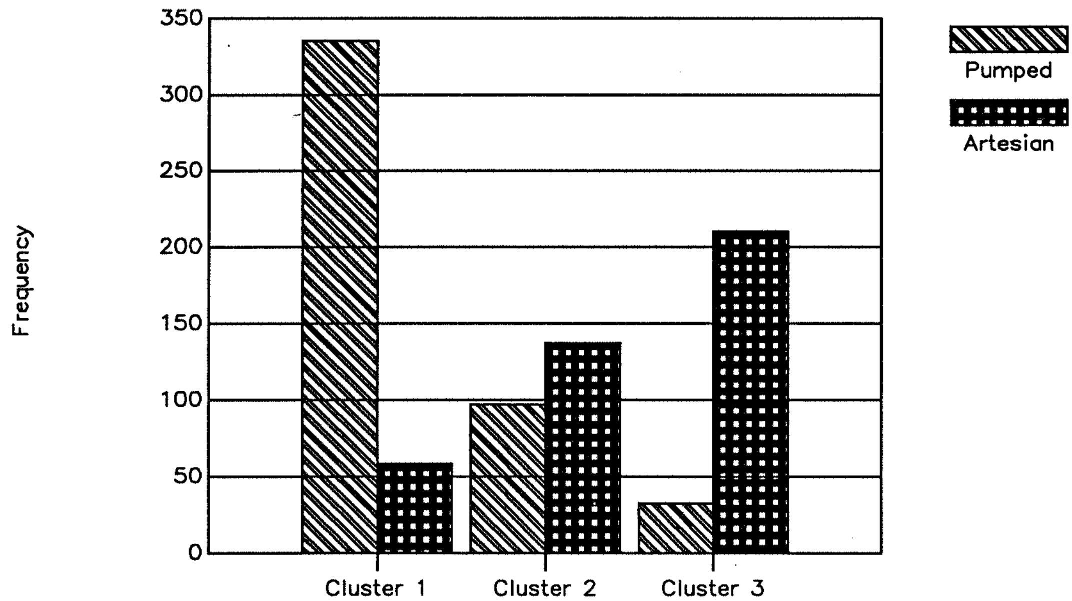


Fig. 5.8 Distribution of tube well types for the three depth clusters.

The first depth cluster is mainly the domain of pumped tube wells. Pumped tube wells which for the larger part may once have yielded water under artesian conditions are found in the second depth cluster together with a still appreciable number of artesian tube wells. The deepest cluster is apparently still dominated by artesian tube wells. Most of the pre-war deep wells abstract groundwater from this zone. It can be concluded that artesian conditions still prevail in the deepest cluster, whilst the second cluster is characterized by declining regional artesian conditions.

From a geological point of view the three clusters must represent regional horizons with substantially better water-transmitting characteristics. The fact that each cluster clearly forms a domain for a particular tube well type points to the presence of less pervious layers acting as separators. However, the connotation 'aquifer' in the sense of a pervious formation capable of holding water and permitting its movement is not very suitable, because one has a fair probability of penetrating these regional horizons without finding a single sandy layer. It is better to visualize the three regional horizons as ill-defined depth zones with a significantly higher probability of containing one or more sandy layers embedded in less pervious clayey materials and capable of yielding water to small capacity wells.

With the conceptual sedimentation model of Fig. 5.1 as the general framework, one may now contemplate the possible geological mechanisms capable of producing layers with an increased sand content. In a humid tropical setting the sedimentation mechanisms which may lead to thin sheet sands with a substantial lateral extent are:

1) coalescing beach ridges, cheniers and sandy tidal flats, or a combination of these, which may have appreciable lateral extension in an E-W direction on the coastal lowlands, but with a doubtful significant N-S orientation. Quaternary geology maps of the Citarum and Cimanuk delta in the lowlands indicate that the extension of coalesced shore bars is limited, particularly in a N-S direction. In the Cimanuk delta both the channel- and beach ridge sands are merely isolated elements embedded in fluvial- and marine clays, and thus not aggregated into bodies with an increased horizontal dimension. The density and widths of buried abandoned delta channels are too small to constitute important aquifers;
2) volcanic and alluvial fans originating in the piedmont areas; in particular, the volcanic fans of reworked pyroclastic materials during times of huge supplies from the hinterland are capable of reaching distances between apex and their lobes of more than 10 kilometres.

In fact the problem of sand deposition is twofold: (a) the only suitable source rocks are the Quaternary volcanics, since the majority of Tertiary rocks are composed of clays and silts, and (b) the transport of sand-sized material across the coastal lowlands and redistribution by a low-energy Java Sea. Major geological processes which act on a regional scale and capable of transporting and depositing sandy layers are the following:

1) (sub)-regional volcanism, preferably with outbursts from several volcanic vents, may produce important and vast volcanic fans such as the widespread Late Pleistocene Volcanic Fan Formation in the West Java lowlands. The material may be airborne or reworked and redeposited pyroclasts. Volcanogenic materials transported as mudflows are known to have bridged distances of tens of kilometres (lahar flows from Bogor reaching the outskirts of Jakarta);
2) erosion and transport of sandy materials under drier climatic conditions, characterized by episodic high-energy transport by ephemeral braided rivers and sheet floods. In the hinterlands erosion processes are likely to be active, which demolishes soils from humid tropical periods and promotes slumping of the planation gravel ve-

neers into river valleys during heavy storms. Another effect which is difficult to assess might be the assumed stronger winds during dry climatic periods, capable of depositing eolian sands (the Late Pleistocene Volcanic Fan Formation appears to contain local eolian sands);

3) episodic tectonic activities along the hinge zone lead initially to steeper gradients in the streams, which may in turn remove the temporarily stored channel gravels and cause coarse sands to accumulate in the lowlands as radial fans. From field surveys in the hinterlands it is apparent that considerable coarse-grained volcanoclasts are stored as channel deposits, derived by dissection of higher planation levels veneered with gravels and breccias. Increased tectonic activity may force these coarse-grained channel deposits out of temporary storage;

4) during drier climatic conditions and a lowered sea level, thus exposing much of the Sunda shelf, the boundaries between erosion and accumulation areas will shift drastically towards the north. This implies that the piedmont plain deposits or volcanogenic fans along the southern periphery of the lowlands will also be subjected to erosion. Terrain slopes on these morphological elements are presumably sufficiently high to induce rill wash during high seasonal sheetfloods. The materials eroded from piedmont plain areas are accumulated further north on former flood plain deposits and marine clays.

From this selection of geological processes, volcanic activities and erosion/accumulation patterns during drier climatic conditions are considered the most likely to produce sand layers far from the hinterlands. Airborne pyroclasts probably form regional horizons of considerable extent, contrary to the random sandy layer encountered in one of the three depth cluster zones. This leaves erosion and accumulation processes during drier climatic conditions as the sole mechanism for sandy material deposition at remote distances from the hinterlands. Volcanic activity thus becomes important for producing source materials to be redistributed by ETA systems during these drier climates.

VI. EXTERNAL FEATURES OF THE COASTAL LOWLANDS

6.1 Introduction

Apart from some very low relief cheniers and beach ridges the northern coastal lowlands of Java seem to be rather featureless at first glance. From the coast to the hilly hinterland an apparently smoothly sloping topography is found in the field. However, more detailed observations do indeed reveal differences in slopes between the southern and northern parts of the lowlands. Furthermore, the drainage patterns are distinctly different; in the southern part dissection of an alluvial plain fringing the hilly hinterlands is evident, whilst in the northern parts the major streams are flowing between levees, partly natural but mostly man-made, above the very flat plain of newly accreted land. Conspicuous are the directions of main stream channel entering the coastal lowlands from the hilly hinterland. These display initial NNE directions, gradually rotating anti-clockwise to N and NNW directions while crossing the coastal lowlands. The build-up of bird-foot deltas displays similar anti-clockwise rotations.

Detailed morphological analysis of the coastal lowlands is largely hampered by the scarcity of good quality topographical maps. The most detailed and reliable topographic map series is the T725 series[1] from the Directorate of Geology, Bandung, with a scale of 1:50,000 and contour intervals of 25 m. Aerial photographs were also made available to the author, albeit for only the kabupatens of Tegal, Brebes and parts of Indramayu. Nevertheless, an attempt has been made to statistically analyse slope vectors of the coastal lowlands. Slope vectors can be derived from benchmark altitudes indicated on the T725 series topographical sheets.

6.2 Analysis of slope vectors in the coastal lowlands

6.2.1 Available map data and statistical procedures

The density of benchmarks shown on the T725 map sheets varies considerably across the coastal lowlands. The highest densities are found in kabupatens Brebes and Tegal and the smallest in Subang. Altitudes of the benchmarks on the T725 series maps are expressed as whole metres in terms of mean sea level. Slope vectors have been determined by fitting two-dimensional linear surfaces to at least four benchmarks. For this purpose a rectangular grid was drawn on topographical maps, chosen in such a way that each grid cell contains at least four benchmarks. To meet this minimum requirement for the number of benchmarks, cells with sizes of 6 km have to be selected for the area east of the river Ci Manuk and larger sizes (up to 10 km) for areas to the west. Slope vectors are thus derived for a total of 88 cells. The general equation of a two-dimensional linear surface is:

$$z = A_e x + A_n y + A_0 + \xi \qquad (6.1)$$

1 Topographic maps, edition 2-AMS (FE) prepared under the direction of CINCUSARPAC by the U.S. Army map service, Far East. Compiled in 1963 from Java & Madura 1:50,000. Original mapping by Topografische Dienst, Batavia.

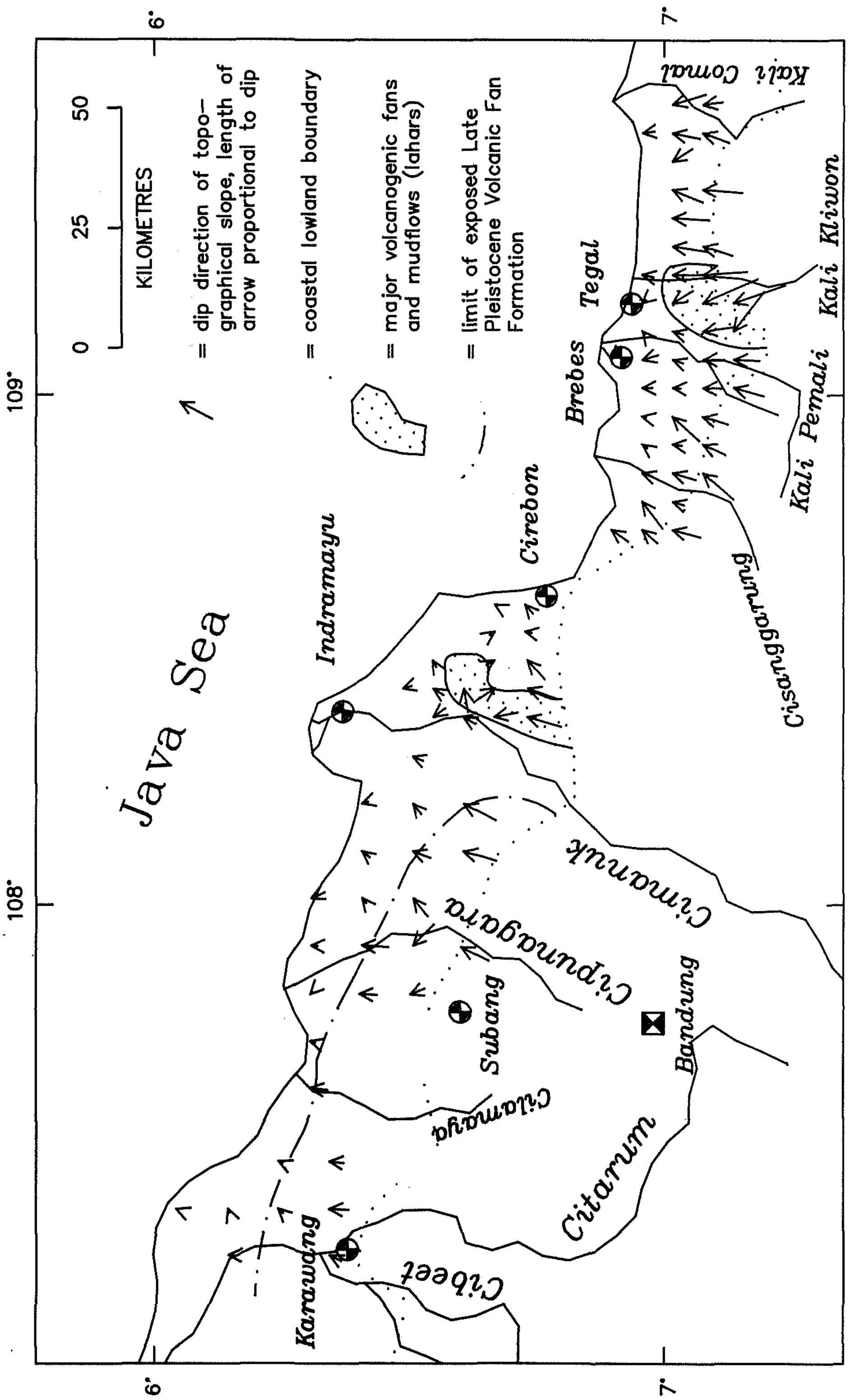


Fig. 6.1 Map showing the slope vectors derived by fitting two-dimensional surfaces to altitude benchmarks within square grid cells measuring 6 to 10 km.

z = dependent variable; elevation of the surface at any x,y grid point with respect to M.S.L.
x,y = benchmark coordinates in grid cell as independent variables.
A_e = regression coefficient, plunge in easterly direction.
A_n = regression coefficient, plunge in northerly direction.
A_0 = regression coefficient.
ξ = random fluctuation.

The slope vector of each fitted surface is simply the resultant of the rectangular component vectors A_e and A_n. General statistics of the number of benchmarks per grid cell and the multiple correlation coefficients of the plane fitting are summarized in Table 6.1.

Table 6.1 Major statistics of the number of benchmarks and multiple correlation coefficients for the 88 grid cells.

Mean number of benchmarks per grid cell	5.72
Standard error	0.23
Mode	5.00
Standard deviation	2.19
Kurtosis	7.85
Skewness	2.60
Minimum	4
Maximum	16
Average multiple correlation coefficient	0.90
Standard deviation	0.13

6.2.2 *Results of the slope vector analysis*

Slope vectors derived from linear plane fitting to the map benchmarks are plotted in Fig. 6.1. The vectors represent the average land surface dip and dip direction for the grid centre, i.e. at the tip of the arrows. The average terrain slope within each cell is shown by the proportional lengths of the arrows.

Slope vector patterns which more or less follow the trend of the major rivers are found in the area of kabupaten Brebes. The anti-clockwise rotations towards the north are better expressed in Brebes than in the Tegal area. A disturbing factor in Tegal is the huge volcanogenic fan of Balapulang. In the eastern part of the kabupaten to the river Kali Comal the general trend reemerges.

In the West Java kabupatens a different situation exists with slope vectors which are much less uniform both in plunge and trend. The vectors in the vast flood plains of the major rivers mostly dip outwards. The topography thus slopes towards poorly drained internal depressions from the river channels. A complicated picture of vectors is found on the eastern side of the river Ci Manuk, caused by a giant late Pleistocene/Holocene lahar flow from the volcano Ciremai which reaches far into the coastal lowlands. A comparison of slope vector trends in the West- and Central Java is shown in the frequency histogram of Fig. 6.2; north is represented by the zero value on the x-axis, the value becoming negative in western directions and positive for easterly trends.

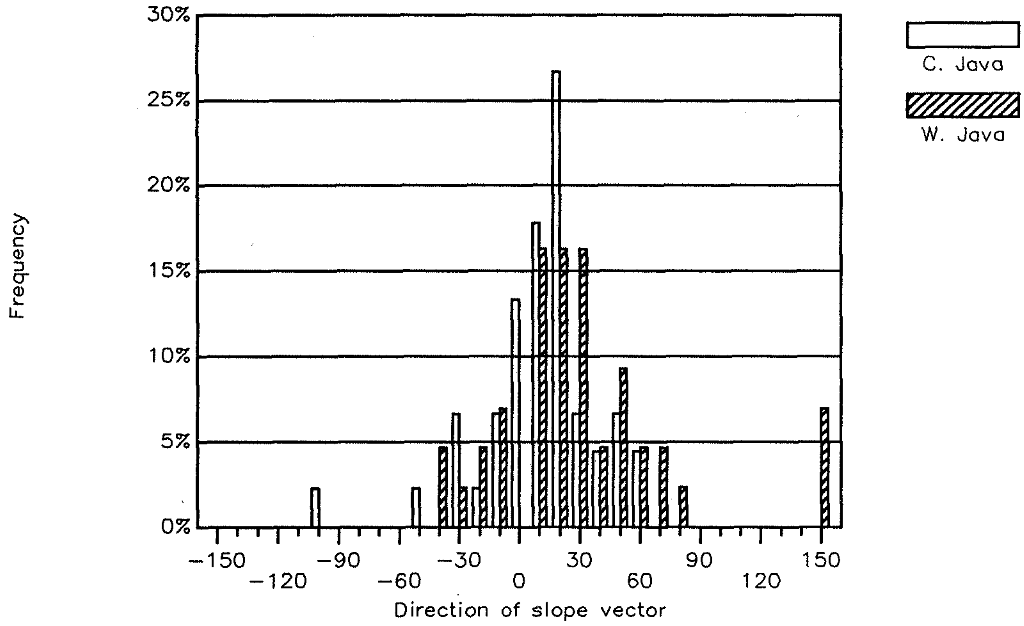


Fig. 6.2 Histogram of slope vector trends in West- and Central Java expressed in degrees west (-) or east (+) from north (0).

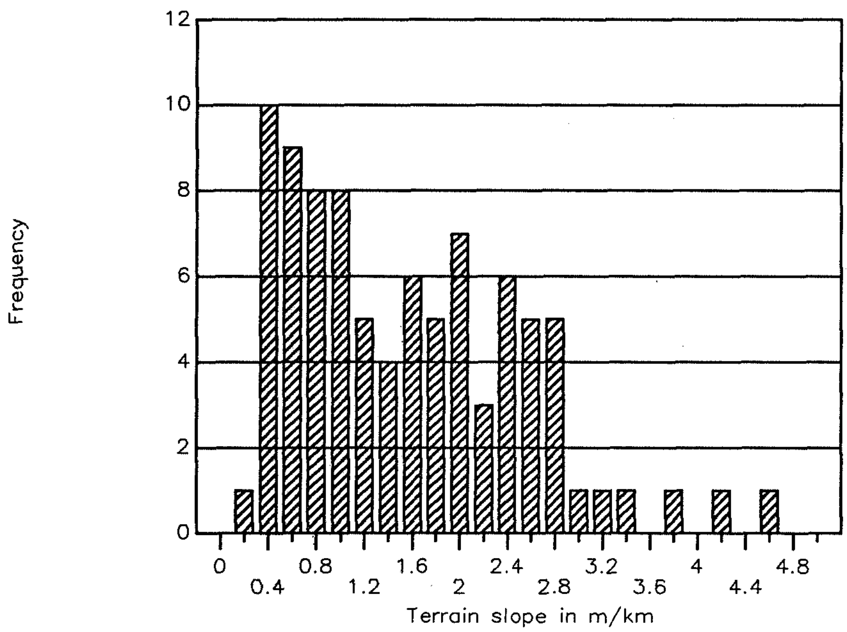


Fig. 6.3 Histogram of the plunge component in slope vectors.

The average trend in Central Java is 4.7 degrees, whereas a value of 26.1 is found for West Java. The variability in dip directions in the sample of 43 vectors for West Java is higher due to the giant lahar flow near Cirebon, with anomalous directions of about 150 degrees. Standard deviations for West- and Central Java are 43.5 and 27.8 degrees respectively.

A frequency histogram of slope vector plunge is shown in Fig. 6.3. Plunges of more than 3 m per km are found on the volcanogenic fan in Tegal. The SPSS procedure 'Cluster' (using Ward's agglomeration method, squared Euclidean distances for similarity measure and sample-oriented Q-mode) is applied to the slope vector data to find plunge groups in the population of slope vectors. The raw plunge and vector trend data have first been preprocessed by log-transformation and Normal(0,1) standardization. Based on the tree diagram of procedure Cluster a number of four clusters are found and listed in Table 6.2. A comparison with Fig. 6.3 shows that the average plunge value for each cluster corresponds fairly well with the local maxima in the bar diagram. The cluster procedure divides the local maximum around 0.6 m/km into two clusters.

Table 6.2 Plunge clusters in the slope vectors expressed as m/km.

Cluster	Cases	Average Plunge (m/km)	St. Dev. Plunge
	25	2.71	0.60
2	16	0.83	0.10
3	27	1.55	0.30
4	20	0.38	0.13

The smallest plunge value of 0.38 m/km is found along the coast on the flat deltaic plains, whereas the main flood plain areas display average plunges of 0.83 m/km in the lower parts and up to 1.55 m/km near the border with the dissected alluvial plains in the south. Average plunge values of 2.71 m/km are found near the border with the hilly hinterlands.

A similar cluster analysis has also been applied to the combination of variables Plunge and Trend of the slope vectors. To assure similar magnitudes of the variables the same preprocessing has been performed as described above. The clusters are listed in Table 6.3 along with reported averages and standard deviations of the unstandardized original data for each cluster. The analysis of variance within groups for both variables listed in Table 6.3 again refers to the standardized data. The high F-ratios of One-Way analysis of variance suggest unequal group means for both pre-processed variables, implying that both variables contribute significantly to the clustering process. At first glance the results of cluster analysis on the log-transformed and standardized variables Trend and Plunge are different from the slope clusters listed in Table 6.2. However, cluster 1 of Table 6.3 corresponds in plunge of slope vectors with cluster 2 of Table 6.2 and likewise cluster 6 in Table 6.3 displays similar plunge values to cluster 4 in Table 6.2. The average plunges of about 1.25 m/km in Table 6.3 seems to correlate with a value of 1.55 in Table 6.2. The anomalous high standard deviation in the variable Trend of cluster 6 is caused by the 150 degrees direction change around the giant lahar flow from Ciremai volcano.

Table 6.3 Major clusters in the slope vectors.

Cluster	Cases	Average Trend (degrees)	St. Dev. Trend	Average Plunge (m/km)	St. Dev. Plunge
1	12	27	12.4	0.90	0.10
2	18	352	12.6	1.25	0.40
3	15	19	4.6	2.20	0.35
4	8	49	13.9	2.10	0.60
5	13	343	19.6	2.85	0.80
6	22	32	60.0	0.45	0.35

Variable	F-ratio	Significance
Trend	6.81	0.00
Plunge	69.95	0.00

More important than deriving possible clusters with group statistics is the translation of the clusters into distinct morphological features of a real world physical setting. Table 6.4 attempts to relate the clusters from Table 6.3 into distinct elements of the coastal lowland physical setting. The six clusters found in the total sample of slope vectors are depicted in Fig. 6.4 in their respective geographical positions. The most distinct groups are 4 and 5. Group 5 is exclusively confined to the Balapulang volcanogenic fan and the radial structures around the outwardly glided Tertiary formations which resulted from Pleistocene collapse of a former Slamet volcanic cone. Group 4 is found only in the surroundings of Ciremai volcano and on land surfaces developed on the Lower Pleistocene Gintung Formation. The dissected alluvial plains along the hilly hinterland are represented by cluster 3, which has a small variability in slope vector trend compared to the other groups. It is this small trend variability which renders the impression of coalescing adjacent alluvial fans having eventually formed a piedmont alluvial plain. Average trends of 19^0 accord well with the initial channel directions of major rivers at points of entry to the coastal lowlands. The variability in slope vector trends in the flood plain belt and the coastal plain/deltaic plains increases considerably. The more uniform slope trends in the piedmont plain belts may be related to the building up of the plain by coalescing segments of alluvial fans with sediment transport mainly in a NNE direction. In flood plain belts, on the other hand, sediment transport during overbank flows produces crevasse splays and layers of silts and clays with sediment transport directions away from of the channel towards the backswamp basins. However, a quality effect of the available benchmark data and density per grid cell cannot be excluded. The number of benchmarks in the flood plain belt becomes less and benchmarks may be situated preferentially at more elevated locations, such as on road verges or on former beach ridges in the coastal plain.

Table 6.4 Correlation between slope vector clusters and morphological coastal lowland units (MCU) in the physical setting.

Cluster	Physical setting
1	NNE sloping lower parts of the flood plains and coastal plain/deltaic plains; variable trends. Situated north of the exposed Late Pleistocene Volcanic Fan Formation (see Fig. 6.1).
2	N dipping southern parts of the flood plain belt or valleys incised in Late Pleistocene Volcanic Fan Formation or Holocene piedmont plains.
3	Dissected piedmont alluvial plains along the hilly hinterlands and erosion surface on Late Pleistocene Volcanic Fan Formation; small variability in dip direction; this cluster is exclusively found in this dissected alluvial plain and exposed Fan Formation giving the impression of an extensive piedmont alluvial plain.
4	Areas underlain by the Pleistocene volcanogenic Gintung Formation and the younger volcanogenic fans originating from Ciremai volcano in Cirebon.
5	Balapulang volcanogenic fan in Tegal and the alluvial plain slopes near the radial structures around Slamet volcano and young alluvial fans in Indramayu.
6	Coastal plain/deltaic plains and lower parts of the flood plain belt and the outer fingers of the giant lahar flow in kab. Cirebon; trend and plunge of slope vectors highly variable.

The trend uniformity of group 3 is still remarkable, since distinct differences exist in these dissected southern parts of the coastal lowlands. In the West Java sector the Late Pleistocene Volcanic Fan Formation consisting of alluvial and volcanogenic fans is exposed over large areas (see Fig. 6.1). This Late Pleistocene Formation constitutes an erosion surface dating from the last glacial with sea level lowering of tens of metres. From Fig. 6.1 it can be inferred that the Volcanic Fan Formation, although covered by Holocene deposits, is found at shallow depths near the present-day coastline; shown also by Rimbaman et al. (1986). The southern parts of the Late Pleistocene Volcanic Fan Formation, adjacent to the hinterlands, are partly covered by Holocene alluvial fans.

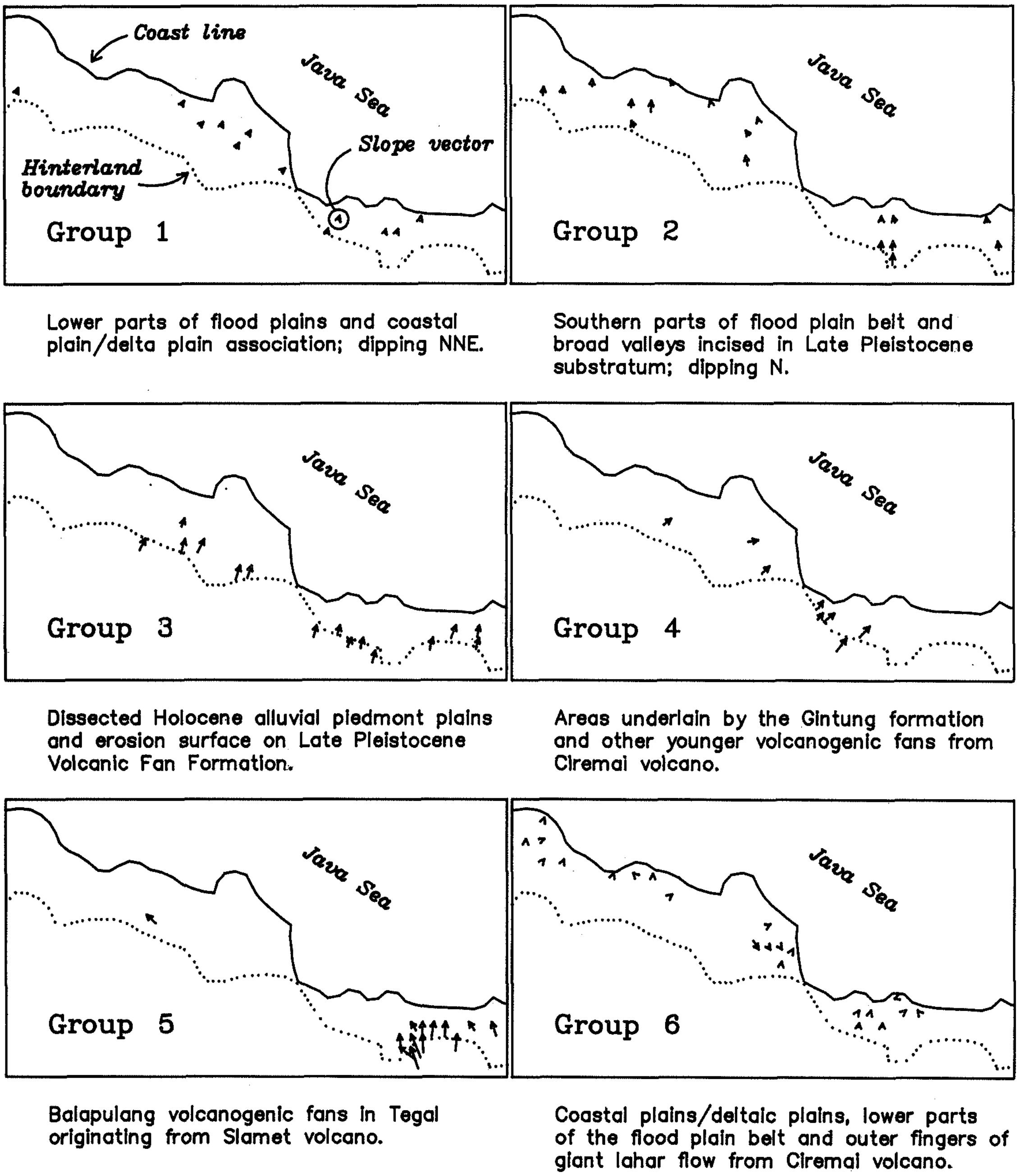


Fig. 6.4 The six groups found by cluster analysis in the sample of slope vectors and their regional occurrence. See also Table 6.4 for more detailed descriptions of physical setting for the groups.

This contrasts with the situation in the Central Java sector in which the Late Pleistocene Volcanic Fan Formation, if present, or a former erosion surface dating from the last glacial is everywhere hidden under a Holocene cover. It is most likely that this effect can be attributed to the difference in N-S lengths of the coastal lowlands. In Central Java the gap between distal parts of alluvial fans and the coastal plain/shallow marine deposits could still be covered by flood plain deposits, whilst in West Java the gap was apparently too large. In West Java river incision took place into the exposed Late Pleistocene Volcanic Fan Formation beyond the distal fan zone, strongly reducing the likelihood of overbank flooding and hence rendering the area prone to degradation. Thus although a conspicuous contrast exists in genesis and geology, the statistical classification analysis does not reveal a significant difference in slope development for group 3 between Central- and West Java.

The Holocene alluvial plains were built up during times when the sediment supply was much greater than today due to regional volcanism in the magmatic arc of Java. The Late Pleistocene Volcanic Fan Formation with the lateritic soil once formed an old land surface, sculptured during the last glacial during low sea levels. A drainage pattern seems to have developed in the last glacial when the Java Sea fell dry (Umbgrove, 1929), with a general flow direction towards the east.

The maximum thickness of Holocene cover is unlikely to exceed 30 m and average values of about 15 m are to be expected. It can be reasoned that the build-up of the piedmont plains must have been influenced by this former Late Pleistocene land surface. Since the piedmont plain sediments were deposited prior to the flood plain- and coastal plain belt, it stands to reason that the outward spreading alluvial fans have been controlled by the dip and in particular the dip direction of this old land surface. The small variability in trend suggests that no correspondence exists between the piedmont plains and the present coastline. It is postulated that the average trend of 19^0 for the piedmont plains reflects the original dip direction of the underlying former land surface. The general trend of anti-clockwise rotations is not so well disclosed by the statistics of clusters 1 and 6. The variabilities in trends are apparently too high, especially in the case of cluster 6. The main reasons for the high variabilities are, as mentioned before, the low density and the data quality of benchmarks and the apparently highly variable slope directions in the flood plain- and coastal plain belt. On the other hand it is remarkable that the slope vectors of clusters 1 and 6 are situated precisely outside the exposed Late Pleistocene Volcanic Fan formation belt. This fact accords with the interpretation of clusters 1 and 6 of being confined to the coastal plain/delta plain complex.

Cluster 2 which represents the flood plain belt, shows some conspicuous slope vectors in Karawang and Subang which are situated in broad valleys filled with flood basin clays and eroded in the Late Pleistocene Volcanic Fan Formation. A remarkable discovery from the slope vector data is the giant lahar flow which descended from the northern slopes of Ciremai volcano in Cirebon. Although mapped on the geological sheet of the Cirebon area the topographical expression, especially the radial fan-like shape, of the lahar in the slope vector data is certainly noteworthy.

The significance of the derived clusters and any misclassification can be further tested by discriminant analysis. In this case the discriminant analysis is performed on the original slope vector trend and plunge data without any pre-processing. As a next step after classification, discriminant analysis may then be used to classify new slope vector samples. In order to test which variable should be entered first in the analysis, the Mahalanobis distance between groups is applied for variable selection. The results of the discriminant analysis are listed in Table 6.5.

Table 6.5 Result of discriminant analysis on the six groups in the slope vectors given by Table 6.3.

Variable	F-ratio	Wilks' Lambda U-stat.	Signif.	Mahalanobis D-squared	Between groups
Trend	7.5	0.68	0.00	0.02	3 and 4
Plunge	59.0	0.22	0.00	0.06	1 and 6

Canonical Discriminant Functions

Function	Eigenvalue	Variance %	Canonical Corr.
1	4.20	92.81	0.90
2	0.33	7.19	0.50

Unequal group means for both unstandardized variables Trend and Plunge are also indicated by the high F-ratios of the One-Way analysis of variance and extreme small levels of significance in the upper part of the table. The Wilks' Lambda, i.e. the proportion of total explained by variance within groups, is inversely related to the F statistic. Disparity among group means for variable Plunge is larger than for variable Trend. The calculated Mahalanobis distance is the smallest distance between groups that are closest. Hence, the larger disparity in group means of variable Plunge is also expressed in the slightly greater value for the Mahalanobis distance. The variable with the greatest distance (D-squared) is then selected as the first variable to be entered in the analysis. For this problem variable selection by means of the Mahalanobis distance is not very critical, since D-squared has the same magnitude for both unstandardized variables indicating similar smallest between-group distances. This effect is also noticeable in the relatively high canonical correlation coefficients for the second linear discriminant function. The number of significant discriminant functions is the same as the number of variables in the analysis, thus no reduction in dimensionality has taken place to describe the differences between the six groups.

Thus far discriminant analysis applied to the original data is not contradictory to the cluster analysis on pre-processed and standardized data.

Another aspect is the misclassification of cases, related to both the original classification by the clustering procedure for standardized data and the effectiveness of the discriminant functions. The result of the classification analysis is shown in Table 6.6.

The percentage of correctly classified cases is 78.4%. Remarkable is the predicted classification of group 1. Group 6, which is interpreted as being slope vectors from the coastal plain/deltaic plains, shows 5 cases which could be classified in groups 1 and 2 This predicted group membership is plausible, since group 6 is interpreted as the coastal plain zone bordering the flood plain zone and hence related to group 2.

Table 6.6 Actual- and predicted group membership.

Actual group	Cases	Predicted group membership 1	2	3	4	5	6
1	12	100.0%					
2	18	11.1%	72.2%	16.7%			
3	15		6.7%	86.7%	6.7%		
4	8			25.0%	75.0%		
5	13		15.4%	15.4%		69.2%	
6	22	9.1%	13.6%		4.5%		72.7%

6.2.3 *Discussion*

The purpose of this chapter so far was to differentiate and describe morphological zoning of the coastal lowlands. First field visits to the lowlands give the erroneous impression of an almost featureless plain, smoothly sloping towards a sudden break in slope at the distinct lowlands/hinterlands boundary. The hilly hinterlands may be formed by Tertiary formations or Quaternary volcanics. However, as previously emphasized, closer examination of the coastal lowlands does indeed reveal differences in slope and surface drainage pattern. Soil sampling with a simple hand auger discloses sharp contrasts in lithology of the alluvial sediments along a N-S profile across the lowlands. Thus a suspected N-S morphological zoning appears to be reasonable, is a logical outcome of field observations and fits into the concept of associations in fluvial environments (Reineck and Singh, 1975).

In this chapter the problem has been approached by analysing a sample of benchmark-derived slope vectors, chosen in such a way that the sample is more or less evenly scattered over the studied parts of the lowlands. The application of multivariate statistical methods resulted in distinguishing six groups in the slope vector sample. A further testing by discriminant analysis indicated that no further reduction in dimensionality could be accomplished, implying that significant group differences exist. These six groups were then interpreted in terms of morphological units for the real-world physical setting. Groups 3, 4 and 5 represent distinct recognizable morphological units, namely the piedmont plains and the volcanogenic fans of Ciremai and Slamet volcanoes respectively. These three groups are all situated in the southern parts of the coastal lowlands bordering the hinterlands. Towards the north the interpretation of slope vector groups becomes more problematic, but is nevertheless still solvable. The flat deltaic plains and newly accreted flat lands are recognizable in group 6, whereas the areas underlain by stiff grey flood plain clays can be classified into groups 1 and 2. The hypothesis of anti-clockwise rotation of the slope vectors going from south to the north is not so well supported by the slope vector trends. The trend variability of slope vectors in the northern parts of the lowlands is too high to draw firm conclusions.

Remarkable and totally unexpected in the slope vector analyses is the well pronounced expression of the dissected piedmont plains and volcanogenic fans. As a second discovery the giant lahar flow at the northern foot of Ciremai volcano must also be mentioned. The cluster analysis discriminates best among groups with the largest between-group distances such as found in groups 3, 4 and 5.

6.2.4 Morphological zoning of the coastal lowlands

Both field observations and the slope vector analyses justify a morphological zoning model with four major units:

1) *Piedmont alluvial plain belt*, with freely drained thin reddish-brown soils in which the pedogenetic characteristics are still weakly developed;
2) *Late Pleistocene Volcanic Fan Formation*, covered by remnants of a thoroughly weathered reddish coloured paleosol with omnipresent mottling;
3) *Lower course overbank flood plains*, covered by soils with little or no development of pedogenetic horizons and clayey soils with seasonal drying and wetting;
4) *Coastal plain/deltaic plains*, covered by soils with little or no development of pedogenetic horizons.

The piedmont alluvial plains are found bordering the hilly erosional hinterlands and form gently sloping alluvial aprons. The sedimentology can be described as laterally coalesced alluvial fans resting unconformably on the Late Pleistocene Volcanic Fan Formation. This depositional belt is omnipresent in the studied Central Java sector but lacking in most parts of West Java. The alluvial fan deposits, with occasional debris flow intercalations, are topped by overbank flood water deposits of clayey fine sands forming the upper terrace. Gravel deposits are in the minority and are related to reworked materials from Late Pleistocene/Early Holocene volcanism. The proportion of volcanogenic materials increases near the large eruption centres of Slamet and Ciremai volcanoes. The provenance of fan sediments consists of these young unweathered volcanogenic materials, but the bulk is made up of erosion products from the argillaceous Tertiary rocks in the hinterland. Dissection of this alluvial apron to a maximum of about 15 m below the upper terrace is evident everywhere.

A number of factors can be mentioned which are considered as decisive in the genesis of this depositional belt of wet fans:

1) the existence of closely spaced streams and brooks draining the eroded hinterlands which consist of practically impermeable Tertiary marine shales, marls and mudstones;
2) the existence of tectonic flexure zones bordering the hilly hinterlands creating abrupt topographic discontinuities;
3) the availability of heavy sediment loads during the regional young volcanic activities at the Pleistocene/Holocene boundary;
4) the violent Am river regimes inducing river bank undercutting and frequent hill side slips, which may release huge sediment loads.

The Late Pleistocene Volcanic Fan Formation is exposed over vast areas in the southern parts of kabupatens Karawang, Subang and Indramayu and is easily recognized in the field by the reddish coloured lateritic soil. Geological maps of the quadrangles Arjawinangun (Djuri, 1973) and Bandung (Silitonga, 1973) attribute a Lower Pleistocene age to these 'tuffaceous sandstones, clays and conglomerates'. The Lower Pleistocene age is considered here as incorrect, based on the plan-horizontal bedding and the presence of this formation at shallow depths beneath the coastal plain/deltaic complex cover. As will be touched on further later, two deep water wells in kabupaten Subang penetrate this Late Pleistocene volcanogenic formation which has a thickness of about 50 m. From the paleontological and lithological descriptions of the wells it is beyond any doubt that this formation does not constitute the base of the Quaternary sediment pile.

Observations by the present author in the area around Jatitujuh (west of the river Cimanuk in kabupaten Indramayu) reveal reddish weathered reworked ash and tephra[2]. At this location near Jatitujuh, the planation surface on this Late Pleistocene formation is evident and dissection during the Holocene has led to a gently undulating topography with partly exhumed paleosol profiles. In a westerly direction, almost to Jakarta, the Late Pleistocene Volcanic Fan Formation and paleosol is topped by an erosional planation surface and dissected by the present-day drainage systems. This general picture is somewhat disturbed by a faint fan-like morphology near the boundary between kabupatens Subang and Karawang, presumably the distal parts of volcanogenic fans which descended to the coastal lowlands in Late Pleistocene times through the valley Purwakarta-Cikampek.

Dissection of the piedmont alluvial plain and Late Pleistocene Volcanic Fan Formation during the Holocene, in all likelihood a rejuvenation without much uplift is probably due to the decrease in sediment load after cessation of the young volcanism. Huge amounts of volcanic materials must have been produced in the Late Pleistocene. This can be deduced from the fact that the hilly hinterlands must have been covered by a veneer of volcanic materials before dissection. Many remnants of this veneer are still present and young volcanic pebbles and boulders make up the bulk of fan deposits in the piedmont alluvial plains (see also Fig. 4.8 for the structural position of the clastic veneers). In the hinterlands of kabupaten Indramayu, consisting of Pliocene formations, remnants of this volcanic veneer are available which are still not attacked by erosion.

Rimbanan et al. (1986) report on subsoil investigations by auger hole drilling in the area of Cilamaya near the coast in the eastern part of kabupaten Karawang. A strikingly similar lithology is found of clays and silts with occasional thin pebble layers, weathered to lateritic soils. Reportedly the upper layers reveal red and bright yellow (Jarosite) mottling[3]. The sedimentary environment is interpreted as eolian, fluviatile and marine. The gypsum crystals in combination with jarosite are similar to those found in the Upper Pliocene Kaliglagah Formation, also a coastal plain environment with marine ingressions, and clearly indicates coastal swamp conditions.

---

2 The weathered and reworked volcanics contain some organic matter. Mottling is nearly always present as grey to pale coloured patches and spots, but the main colour is always red to reddish brown. The original sediment is hard to recognize but appears to be reworked tephra and perhaps airborne ash. Subangular pebbles (up to 2 cm) occur erratically in thin horizons and are not yet weathered so far as to become friable. Pedogenetic concretions, mm- and cm-sized, of calcium carbonate were encountered.

3 Mottling becomes less at depths of more than 2 m. Small subangular pebbles are also found in thin horizons. Concretions of iron and manganese oxides and calcium carbonate concretions are mentioned. Surprisingly, a single mollusc shell and gypsum crystals were found.

Interesting lithological descriptions of the Late Pleistocene/Early Holocene Volcanic Fan Formation are given on the geological map sheets for the quadrangles Bekasi (Koesoemadinata and Situmorang, 1985) and Batujaya & Galian (Koesoemadinata et al., 1985), forming part of the Systematic Quaternary Geologic Map of Indonesia, scale 1:50,000. Both sheets target the western kabupaten boundary area of Karawang. The descriptions mention tuff, tuffaceous silt and sand and tuffaceous clay, gravelly, sticky and distinct reddish brown mottling. The age is considered to be Late Pleistocene and partly Early Holocene, whilst the sedimentary environment is thought to be fluviatile, eolian, and volcanic. The Bekasi sheet reports a 'Sheet deposit of volcanic origin' and further a very poorly sorted alluvial fan deposit of conglomeratic sandstones underneath the tuffaceous clays and silts. On these sheets the Late Pleistocene Volcanic Fan Formation is omnipresent and forms the stratigraphic base for the overlying flood- and coastal plain deposits. From the foregoing three conclusions can be drawn:

1) the Late Pleistocene/Early Holocene Volcanic Fan Formation is uniform with respect to lithological character and soil forming processes;
2) the sedimentary environment is fluviatile and eolian with some local patches of marine/coastal swamp deposits;
3) the top of the Volcanic Fan formation, now partly covered by Holocene deposits, once formed a land surface during the last glacial period.

Most interesting is the eolian character of the sediments in relation to a reconstruction of the original environment and climatic conditions. Eolian deposition and sheet deposits are not expected in a densely vegetated coastal lowland with tropical forests, or as was described by a British officer in 1813 as being covered with swamps and jungles which were hard to pass even on horseback (in Van Schaik, 1986, p:54). Another striking fact is the vast extent of this Late Pleistocene Formation as alluvial/volcanogenic fan deposits so far from the volcanic provenance areas. The distal segments of the Holocene fan deposits in the piedmont alluvial plain, buil. ıp under humid tropical conditions, do not reach such extensions as was discussed in Chapter 5. The most logical explanation in this respect is deposition under drier savannah-like conditions with a strongly reduced vegetation cover to permit removal of fine material by wind and sheet erosion and to thus sculpture the planation surface.

The lower course overbank flood plain deposits are built up from vertical accretion flood basin deposits, channel sands and levees. The flood plain deposits overlie the Late Pleistocene Volcanic Fan Formation and encroach upon the coastal plain/deltaic plain deposits. Only in those situations in which the flood plain deposits directly overlie the reddish weathered Volcanic Fan Formation can the boundary be readily mapped. In kabupatens Cirebon, Tegal and Brebes without an exposed equivalent of the Late Pleistocene Volcanic Fan Formation, the boundary can be ascertained in the field only by auger hole drilling. The same applies for the boundary on the northern side of the flood plain belt with respect to the coastal plain/deltaic plain deposits. The variability in trend of slope vectors for this flood plain belt is not easily recognized in the field. However, the outward sloping flood basins flanking the larger rivers such as the Cimanuk and Citarum are certainly noticeable in the field. Most of the villages are situated in this flood plain belt on the channel sands and levees. Ribbon development of the villages is obvious. Presumably without being aware of the physical setting the local inhabitants generally know exactly where to find suitable building sites, such as on former channel sands, levees and beach ridges, because of the poor foundation characteristics of the predominantly montmorillonitic flood plain clays. Before human dwelling and subsequent reclamation, vast poorly drained internal basins covered with backswamps were found in this belt. In many parts a natural secondary drainage system has developed in the inter-channel areas of large rivers. The flood plain belt is lithologically built up by invariably homogeneous stiff grey clays and silts, always mottled, with organic matter and often with calcium carbonate nodules and occasionally cm-bedded minor sand lenses.

The fourth major morphological zone is the coastal plain/deltaic plain complex bordering the shallow microtidal Java Sea. It comprises the extensive swampy coastal flats of emergent or near-emergent surfaces, with or without beach ridge complexes, and the delta plains with active and abandoned channels. The boundary with the flood plain belt is not always well defined on morphological grounds, the more so as the flood plain clays gradually encroach upon the coastal plain/delta plain deposits. In this setting typical coastal plain deposits such as mangrove swamps and near-shore deposits may be already blanketed by a thin veneer (up to an average maximum thicknesses of 4 m) of flood plain clays. Although hidden from view by the flood plain clays the average terrain slope resembles that of the unblanketed coastal plains. As a result, statistical slope vector analysis is not likely to discriminate between flood plain clay covered and uncovered parts of the coastal plain/delta plain complex. The most logical physical boundary between the flood plain belt and the coastal plain/delta plain complex is the point where: (a) a change of terrain slope occurs and (b) the underlying marshy coastal plain deposits pinch out. On the southern edge of this boundary the flood plain deposits rest directly on either the Late Pleistocene Volcanic Fan Formation or the piedmont alluvial plains, whereas on the opposite side thin flood plain clays are underlain by coastal plain deposits.

The shoreline reflects the two sedimentary units of cuspate or arcuate shorelines in the interdeltaic areas and the protruding bird-foot type configurations of the shoreline near distributary mouths. The interdeltaic parts with numerous small streams but devoid of any sizable delta, may closely resemble clastic shorelines with longshore drifts and wave-induced deposition of beaches, cheniers and sandy tidal flats. Delta types fall into the class of fluvial-dominated deltas which is characterized by a minimal interference by basin processes. Coastal erosion may occur along interdeltaic shoreline stretches devoid of river outlets due to starvation of sediment. On the whole, however, rapid progradation of the shoreline takes place and may attain spectacular values of more than 100 m per year (van Bemmelen, 1949 and Bird, 1984) for the distributary lobes. Average values of land accretion in the interdeltaic parts, derived by comparison of old maps with recent satellite images, may reach tens of metres per year (Tjia et al., 1968, Hehanussa and Hehuwat, 1979).

The available Quaternary geological maps of Koesoemadinata et al. (1985), Janssen & Dam (1985) and Rimbanan et al. (1986), define five major mappable sedimentary units:

1) the Late Pleistocene/Early Holocene Volcanic Fan Formation of weathered volcanogenic materials;
2) shallow marine deposits of fine bluish grey clays;
3) tidal flat and near-shore deposits of alternating clay and thin silt/sand layers;
4) mangrove swamp deposits of humic clays alternating with silt and sand layers;
5) beach- and beach ridge deposits consisting of sands and silty sands;
6) flood plain deposits of firm grey clays and humic clays;

7) narrow fluvial channel deposits with sands and silty sands in the top.

The general structure and stratigraphic sequence of the Holocene deposits consists of mangrove swamp-, near-shore- and marine deposits overlain by flood plain clays and irregular beach ridge complexes; a typical progradational sequence. In the active deltaic areas the marine deposits are topped by flood plain clays, whereas in the interdeltaic areas a tendency is noticed for marine deposits to be irregularly overlain by coalescing beaches, beach ridges and chenier complexes. Holocene marine deposits are found far inland below the flood plain clays, with the top of the deposits at a maximum of 4 m above present mean sea level. This position of the marine deposits fits into the concept of a higher relative sea level (4 to 6 m) at about 4,500 years BP for the Java Sea, prior to the hydro-isostatic effects of continental margin uplifts relative to the ocean basins in these regions. Thus slightly higher than the 2 m predicted by Clark et al. (1978).

6.2.5 *Hydrogeological implications of sediments found in the four morphological zones.*

The last part of Chapter 4 on regional stratification in the coastal lowlands ended with a discussion on the possible sedimentary mechanism which may lead to thin sheet sands with a substantial lateral extent. Field experience, old well logs and many other groundwater resources reports indicate the erratic distribution of thin water-transmitting layers. The statistical analyses on well depths revealed three fundamental depth zones from which tube wells are withdrawing groundwater. The description of the morphological zoning so far and the detailed descriptions of the sedimentary units from Late Pleistocene to Holocene times may now be used to shed more light on the formation of these sheet sands.

In a humid tropical setting such as during the Holocene epoch, the majority of sedimentary units with vast lateral extent consisted of low-permeability clays (hydraulic conductivities less than 10 cm/day) such as the fluvial flood plain- and marine clays. The more permeable sandy units are in the minority and are built up by narrow fluvial channel sands, coalescing beach sands, tidal flat sands and beach ridge complexes. In particular, the last unit may produce extensive sheet sands which extend for several kilometres in a N-S direction and tens of kilometres in an E-W orientation, such as found along the coast in the western part of Karawang. However, beach ridge complexes as isolated ridge forms are not continuous and may behave hydrogeologically similar to fluvial channel sands. The fluvial channel sands, as the remaining lithological unit with favourable permeabilities, may reach widths from a few tens to more than a hundred metres. Their occurrence however, embedded in the flood plain clays, is too erratic in a horizontal plane to be significant as a regional permeable horizon. The conclusion must be that only under special conditions of sufficient sand supply and adequately strong wave-induced processes will sheet sands be formed under a humid tropical climate by coalescing beach sands and ridges.

Compared with the clayey units of the Holocene the hydrogeological characteristics of the Late Pleistocene Volcanic Fan Formation are much more favourable. Even in the weathered and mottled top layers hydraulic conductivities are in the order of 1 to 2 m/day, which is sufficient to yield groundwater to numerous dug- and tube wells. It is the vast extent of this unit and the uniform lithology which provides the strong contrasts with sedimentary units produced during the Holocene.

Table 6.7 Summary of hydrogeological units in the coastal lowlands built up by sedimentary units and soil horizons.

Hydrogeological unit	Geometry	Sedimentary environment	Extension	Expected permeability
flood plain clays	sheets/blankets	fluvial, vertical accretion	omnipresent	very poor
channel silts, sands and gravels	tabular, shoestring, ribbons, dendroid	point-bars, channel lag, channel fill	patches near fossil deltas	good
wet and semi-arid alluvial fans	wedge-shaped, radial fan	invariably near hinterland border	local patches, may merge into aprons	fair to good
overbank floodwater deposits of fine clayey sands	sheets/blankets	piedmont alluvial plains	omnipresent	fair to poor
fluvial, eolian reworked volcanic materials	sheets/blankets	during glacials with low sea levels under drier conditions	omnipresent	fair
sheetflood deposits	sheets/blankets	during glacials with low sea levels under drier conditions	omnipresent	fair
volcanogenic fans and lahars	wedge-shaped, radial fan, tabular	fluvial reworking after major outbursts	near major eruption centres only	fair to good
airborne volcanic ashes	blankets	terrestrial and marine	very extensive	poor
tephra	prisms, fans	terrestrial and marine	near major eruption centres only	poor to fair
clayey lateritic paleosols	blankets, belts, pods	terrestrial	omnipresent	poor to very poor
offshore shelf mud blankets	sheets/blankets	open shelf, settling from suspension	very extensive	very poor
shallow marine muds	sheets/blankets	open shelf to near-shore agitation by wind/waves	very extensive	very poor
near-shore, tidal flat muds and fine sands	tabular, wedge shaped	near-shore to littoral	very extensive in one dimension	very poor
mangrove deposits	tabular, prism ribbons, pods	coastal swamps	local patches	very poor
coalescing beaches beach ridges and chenier complexes	sheets, blankets, tabular, shoestring, ribbons	littoral	near the larger deltas	good

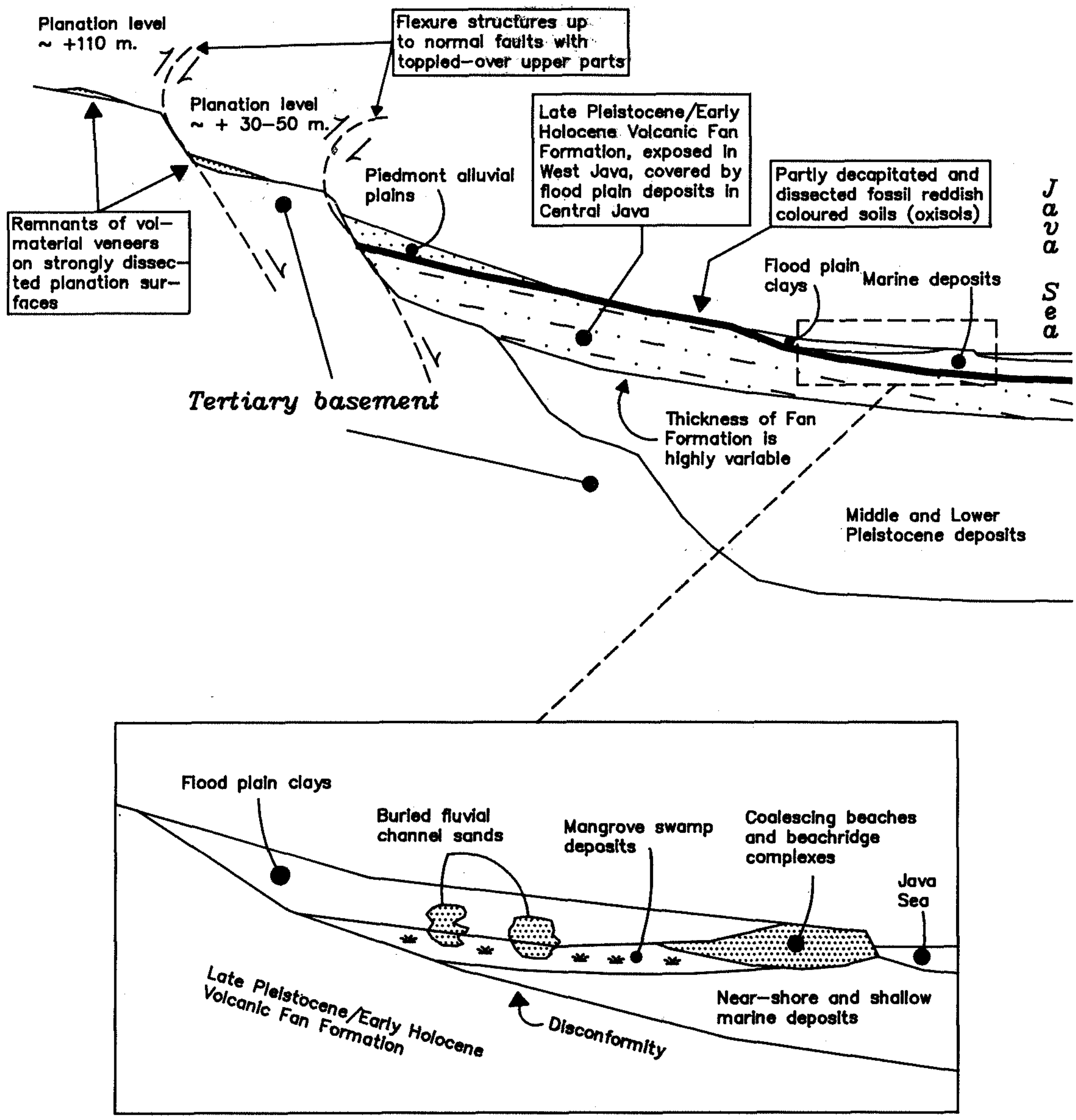


Fig. 6.5 Typical coastal lowland cross section showing the sedimentary units embedded in a basin framework (inset modified after Koesoemadinata et al., 1985, Janssen et al., 1985 and Rimbaman, 1986).

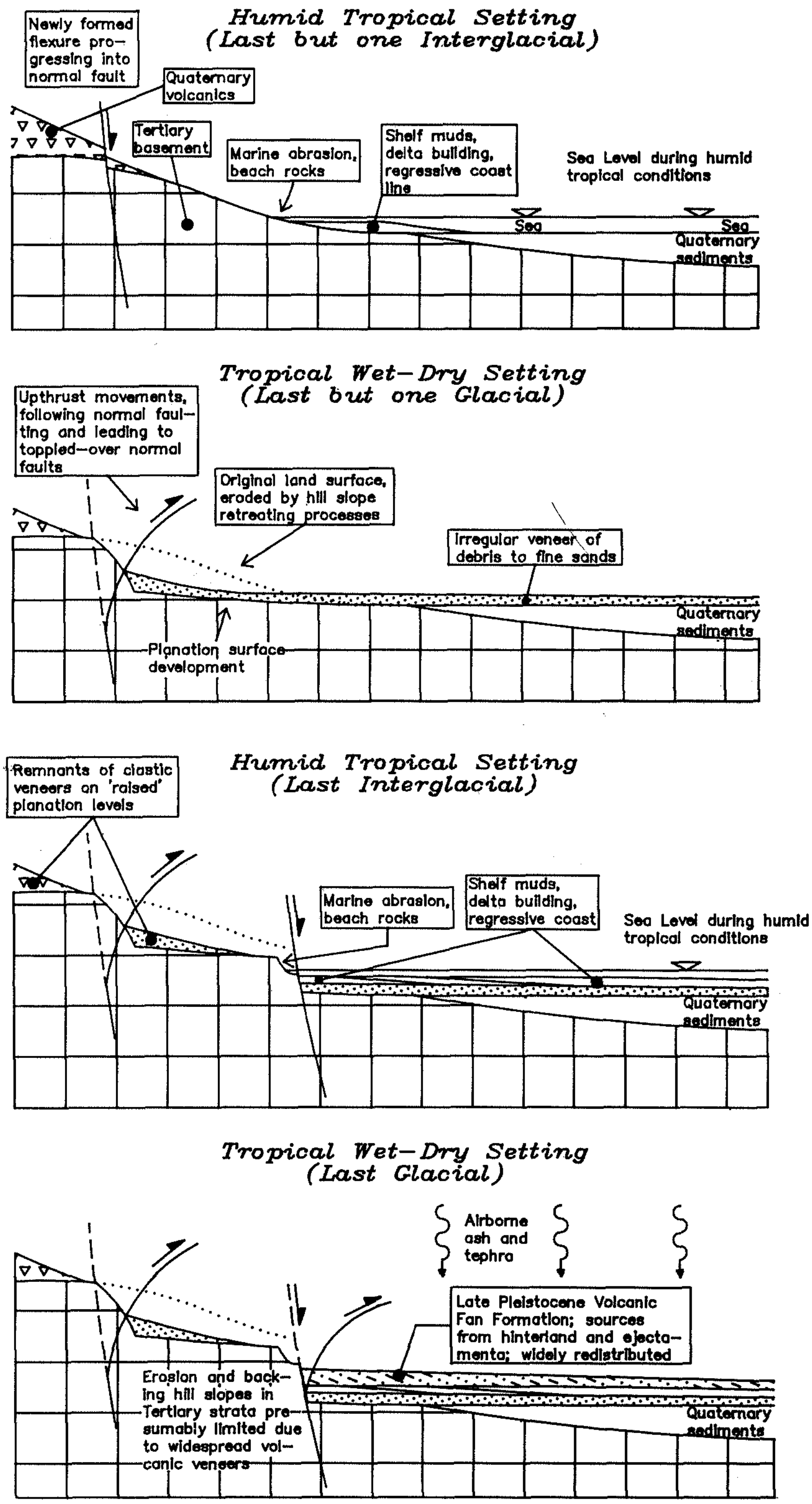


Fig. 6.6 Diagram showing the assumed sequence of geological developments in the coastal lowlands from the last but one interglacial to the last glacial period, prior to the Holocene developments shown in Fig. 6.5.

Entirely different processes of transport and sedimentation must have been active during the deposition of this Volcanic Fan Formation, processes which are thought to have predominated during the more arid climatic conditions of the last glacials. From this discussion it then follows that vast extensive permeable zones are unlikely to have been produced by local beach and beach ridge buildup at the shorelines, but more by a combination of (a): adequate sediment supply from the hinterland and, (b): a deposition mechanism with great lateral extent. Large sediment supplies occur only during major volcanic outbursts leading to heavy stream loads spreading as fans or sheet floods, such as in the piedmont alluvial plains, and airborne tephra. The thin blankets of sheet flood deposits overlying the Late Pleistocene Volcanic Fan Formation, as mapped on the Quaternary geologic map of Bekasi (Koesoemadinata, 1985), support the idea of a deposition mechanism with great lateral extent. The final discussion of Chapter 5 lists the major geological processes which may lead to deposition of regional scale horizons with substantially higher permeabilities than the enveloping clayey strata.

A summary of the sedimentary units which are thought to be present in the coastal lowlands and their respective hydrogeological characteristics is given in Table 6.7. The idealized cross section through the coastal lowlands displayed in Fig. 6.5 attempts to summarize the major sedimentary units and their position in the basin framework. It does not automatically imply from this general cross section that the units are always present. The main difference between the coastal lowland development in West- and Central Java is the gap between the piedmont alluvial plains and the flood plain belt in West Java; whilst in Central Java the flood plain deposits overlie the distal parts of the alluvial plains.

The assumed geological developments, in particular the faulting patterns and forming of planation surfaces during the sequence of climatic fluctuations, are shown in Fig. 6.6 to start from the last but one interglacial. The lowest cross section represents the situation during the last glacial in which most of the Late Pleistocene Volcanic Fan Formation has been deposited, just prior to the Holocene sea level rise and deposition of the lithological units as shown in Fig. 6.5.

An important implication for the hydrogeology of the Quaternary basin is the recurrent sequence of extensive permeable horizons. These are deposited during drier climatic conditions or regional volcanic activities, are overlain by marine clays and swamp deposits and finally capped by stiff homogeneous fluvial clays. Since this cyclic sedimentation is thought to be controlled by climatic changes in combination with regional magmatic activities, thicknesses of the cycles are thus a function of material supply, basin subsidence by sediment loading and tectonic movements in the hinge zone of the sedimentary basin.

VII. GROUNDWATER SYSTEMS IN THE COASTAL LOWLANDS

7.1 Introduction

A previous chapter concerning statistical analyses of tube well depths highlighted the main characteristics of the northern coastal lowlands of Java. The area can be summarized as being devoid of regular and homogeneous aquifers in the sense ot detectable lithological discontinuities having a regional extent from one well to another. Instead of ideal aquifers, groundwater is tapped from ill-defined depth zones which show higher permeabilities than the enveloping sediments. These more permeable horizons are hard to detect during field surveys at a local scale but they nevertheless do appear in statistical analysis of well depths on a regional scale.

The second main characteristic of the groundwaters is their highly variable chemical quality. Qualities may differ over small distances, over intervals of time and between two points both vertically and horizontally within an aquifer. A wide variety of groundwater qualities is generally encountered during well drilling. Even far from the present-day coastline highly saline groundwaters are found in shallow aquifers which are positioned well above sea level. Multiple layering of various groundwater qualities may occur, which may terminate abruptly. High salinities may be present, but surprisingly enough pure seawater was never encountered in any of the 3,357 surveyed wells.

The inexperienced field surveyor is faced with an extreme heterogeneity of well depths, groundwater qualities and irregular static hydraulic heads, which are difficult to explain by classical coastal groundwater hydraulics. Most reports on groundwater situations in coastal lowlands are limited to descriptions only, without contemplating the distribution patterns of water chemistry and their genesis. Examples of recent detailed studies combining flow systems and hydrochemistry in coastal environments have been presented by Stuyfzand (1986, 1988), De Ruiter (1988) and Engelen et al. (1988).

In this chapter it will be shown that, notwithstanding the irregularities in water quality, consistent groundwater systems can still be distinguished. Since the principal aim of the initial field surveys was to prepare groundwater availability maps on a kabupaten scale, the groundwater situation will be likewise depicted in a series of N-S cross sections and discussed against the framework of each of the six surveyed kabupatens.

7.2 General hydrological background characteristics

For the sake of completeness the general characteristics of rainfall and evaporation have to be reviewed. A general description of the climatological conditions has been given in Chapter I. Figures 7.1a and 7.1b depict the average annual rainfall depths for the studied part of the coastal lowlands. The general rainfall depth pattern shows an increase with topographical altitude. The 1,500 mm isohyet in West Java runs close to the southern border of the coastal lowlands. Practically all the broad coastal lowlands in Karawang, Subang and major parts of Indramayu receive annual rainfall depths of less than 1,500 mm. The narrower lowlands in kabupaten Cirebon receive appreciable more precipitation, probably because they are closer to the zone of orographic precipitation.

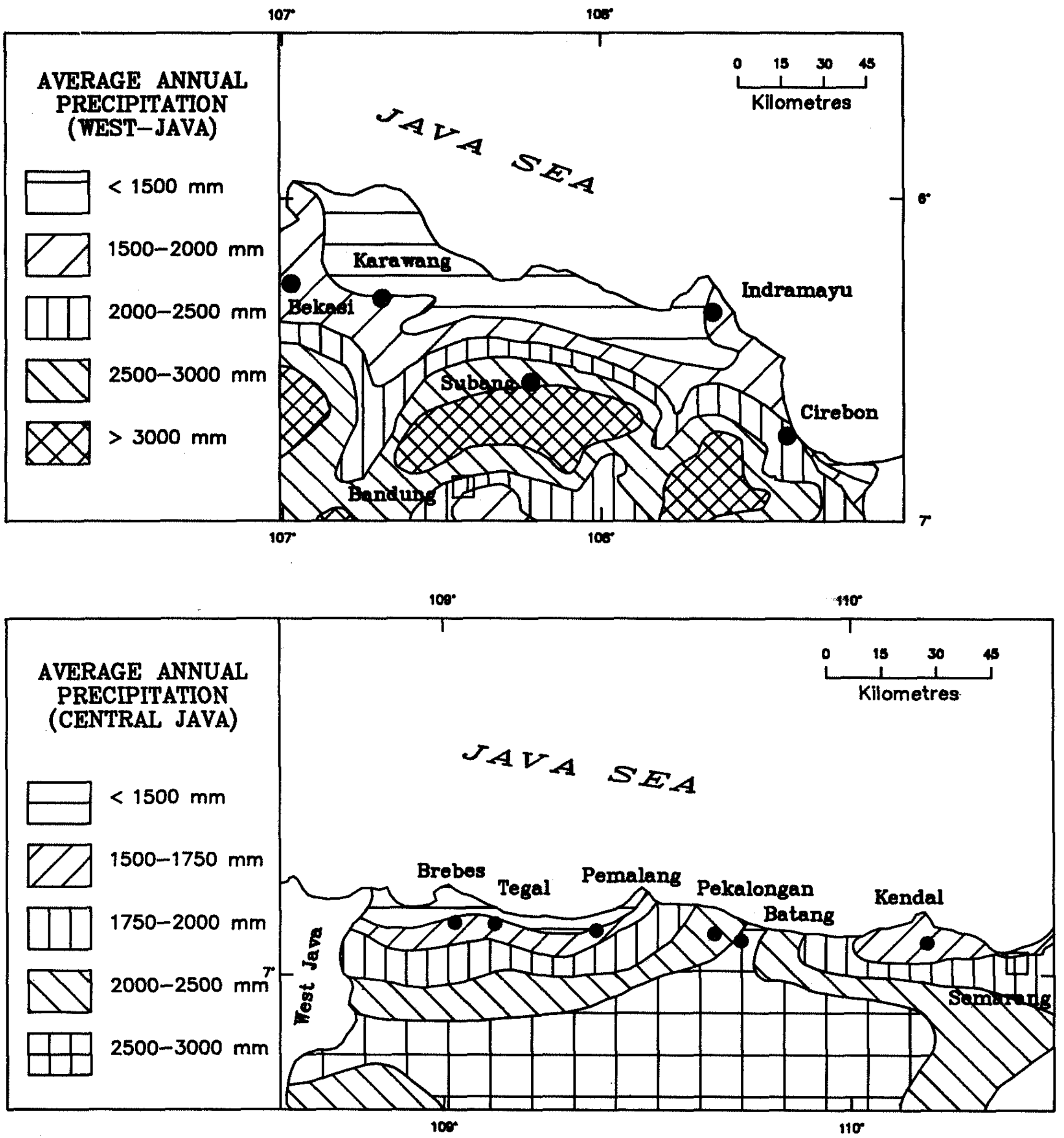
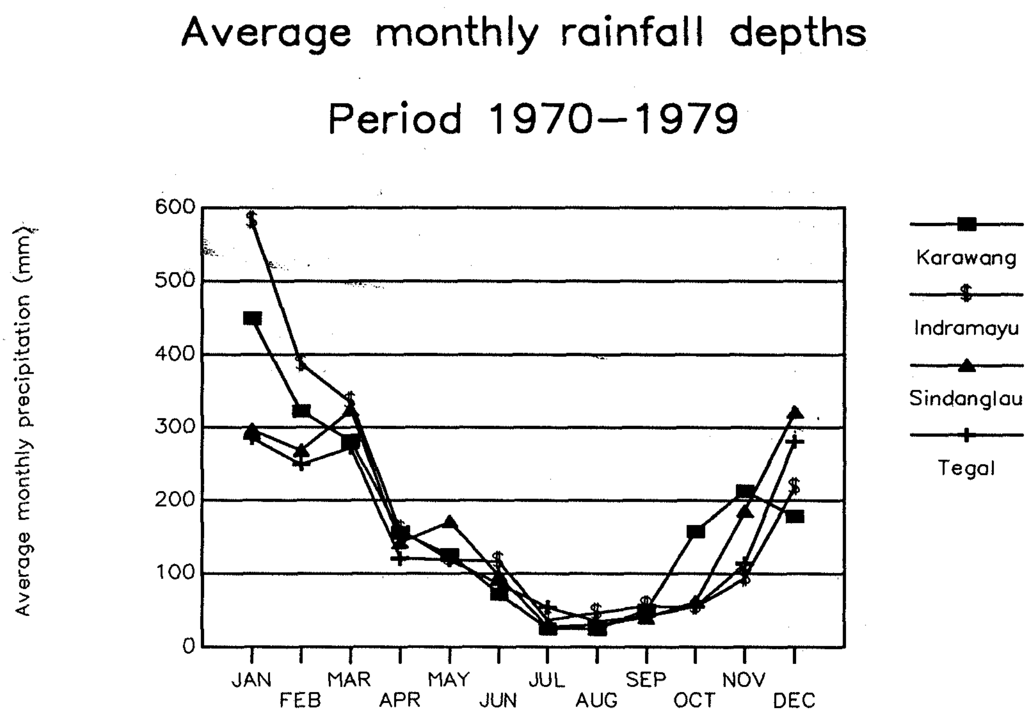


Fig. 7.1ab Average annual precipitation depths (mm) for the coastal lowlands in West Java (a) and Central Java (b), modified after I Made Sandy (1982).



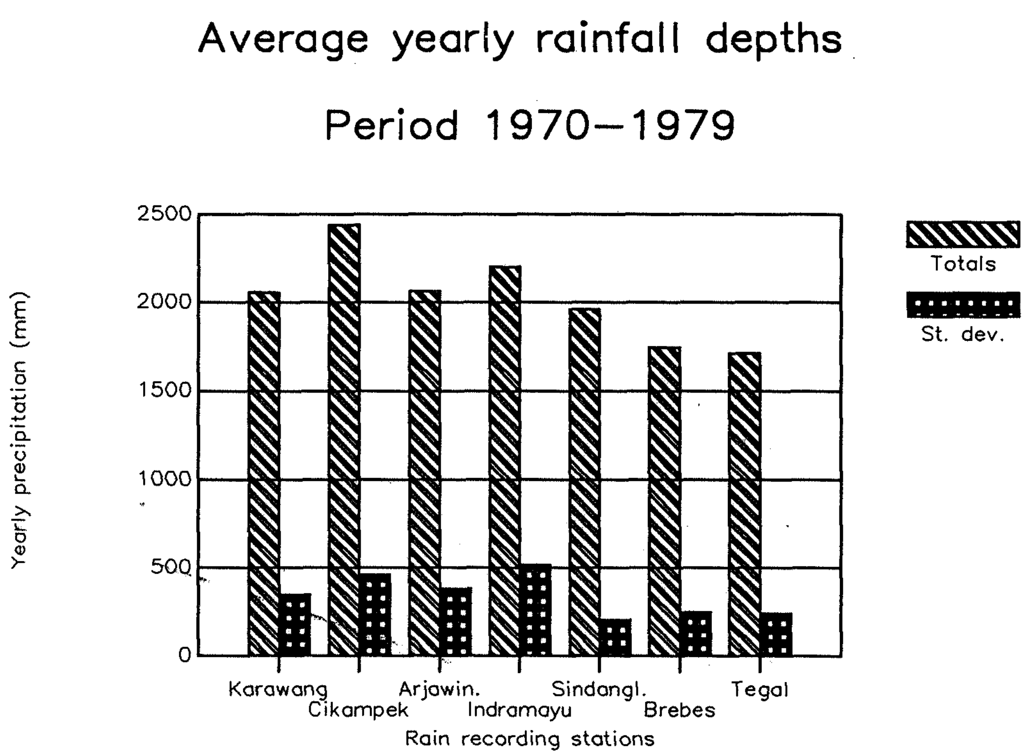


Fig. 7.2ab **Average monthly rainfall depths (a) and average yearly rainfall depths (b) during the period 1970 to 1979 for recording stations in the coastal lowlands.**

The coastal kabupatens in Central Java exhibit a similar isohyetal pattern, for the larger part controlled by the topography.

Average depths of monthly precipitation, calculated over the period 1970 to 1979, are plotted for several stations in the coastal lowlands. The station Sindanglaut is located in the eastern part of kabupaten Cirebon. Noteworthy is the contrast in monthly rainfall depths between the wet (November to March) and dry seasons (April to Oct). Morley (1981) classifies the rainfall regimes in the northern and eastern parts of Java as 'dry season marked', contrasting strongly with the everwet parts in Sumatra and Borneo. Fontanel & Chantefort (1978) label the northern coast of Java to the south of western New Guinea as a 'dry season' regime. These dry season regions represent only 12% of the area of the archipelago and are situated between 6 and 10^0 latitude south; those latitudes influenced by the continental trade-winds originating from the Australian anticyclone during the southeast monsoon. During the north or northwest monsoon the entire region of the archipelago is influenced by maritime trade winds. The marked dry season is reflected in the monthly rainfall depths displayed in Fig. 7.2a.

Average yearly rainfall depths over the same period (1970-1979) for seven low-lying rain recording stations distributed over the coastal lowlands are displayed in the bar diagram of Fig. 7.2b. The diagram suggests a slightly higher precipitation depth and standard deviation for the stations in West Java.

Evapotranspiration values for the coastal lowlands are reported by IWACO (1987b) to be 1,600 mm/year for the area near Bekasi. Based on a water balance study of 25 major streams in West Java, IWACO (1987a) arrives at an average evaporation value of 1,322 mm/year. Binni & Partners (1982) make mention of similar values of potential evapotranspiration for short grass of about 1,700 mm/year for the coastal lowlands in kabupaten Tegal. It is obvious that with these average evapotranspiration values a precipitation deficit is experienced during the months May to September.

7.3 *General field methodology, data collection and processing*

In general outline the systematic water well surveys in the coastal lowland kabupatens consisted of extensive field visits to most of the villages. Practically all kecamatans (an administrative subdivision of a kabupaten) in the coastal lowlands area of the six surveyed kabupatens have been visited. A visit to a village (desa) was aimed at gaining a global impression of the water supply situation from wells in particular. Three types of wells are found, viz.: (a) open dug wells, (b) hand-pumped tube wells without any screen, and (c) large diameter wells equipped with several screens. If the water supply situation from wells was not too problematic in terms of high groundwater salinities, only a few wells were measured by recording the common parameters such as depth, temperature, electrical conductivity of well water, artesian flow, discharge etc. However, highly anomalous situations with varying groundwater salinities have been surveyed in detail. In line with remarks in preceding chapters, situations in which domestic water demand is met by omnipresent fresh groundwater resources is the exception rather than the rule.

To complement the field well data, a total of 659 water samples were collected for further chemical analyses. Samples have been drawn mainly from tube wells and were stored unfiltered in one-litre polyethylene bottles. Alkalinity analysis by titration and pH measurements were usually performed directly in the field. The final chemical analyses for samples from the kabupatens in West Java took place at the chemical laboratory of the institute LIPI in Bandung and later for the Central Java kabupatens at the laboratories of the Faculty of Geography of the Gadjah Mada University in Yogyakarta and the Institute of Earth Sciences, Free University in Amsterdam. Upon arrival from the field the polyethylene bottles were stored under refrigeration and analysed within two weeks of sampling. Chemical analyses comprised the analytical concentrations of the major constituents: Ca, Mg, Na, K, SO_4, HCO_3 and Cl. Laboratory results and procedures were always checked by incorporating one standard sample with every nine field samples. Only those analyses with ionic balance errors less of 10 percent were accepted. The main objective of the chemical analyses and subsequent data processing was to arrive at simple hydrochemical classifications, thus enabling groundwaters with more or less similar chemical characteristics to be detected and defined.

The method for classifying the chemical analyses into similar types of hydrochemical facies was that developed by Stuyfzand (1986). The classification system is based on four main parameters, viz.: (1) the chloride content, (2) total hardness, (3) dominant cations and anions and (4) the sum of Na, K, Mg corrected for a contribution of sea salt (see Appendix I for details). The cross sections are based mainly on the hydrochemical data (see Appendix II), complemented by the regular well data such as electrical conductivities. As the locations of the surveyed wells are not evenly scattered over the kabupaten areas, map cross sections have been chosen in the vicinity of the major well clusters. By adopting a west to east direction the first kabupaten to be discussed will be Karawang in West Java.

The cross sections are complemented by streamlines of groundwater flow, determined by applying the two-dimensional, steady-state groundwater model FLOWNET (van Elburg et al., 1987). This model, developed at the Free University of Amsterdam, is based on a finite-difference scheme and is capable of modelling complex geometric cross sections to produce stream- and equipotential lines and travel time steps for imaginary water particles.

7.4 *Kabupaten Karawang*

7.4.1 *General physical setting*

The conspicuous morphological characteristic of the elongated kabupaten of Karawang is the protruding coastline around a former lobate delta of the river Cimanuk (see Fig. 7.3). This river, draining a vast catchment (6,625 km^2) in the central volcanic zone of West Java, enters the kabupaten in the south and flows along the major part of the western kabupaten boundary with Bekasi. The present-day active Citarum delta is mainly developed in the neighbouring kabupaten Bekasi. A confluent of the Citarum, the river Cibeet forms the remaining part of the western kabupaten boundary with Bekasi. Another important river, the Cilamaya with a drainage basin of 2,500 km^2, flows along the eastern kabupaten boundary.

South of the main road from Karawang to Cikampek a hilly area is found in which Pliocene and Miocene rocks are exposed. Most of the hill summits appear to fit the planation level of about 110 m altitude.

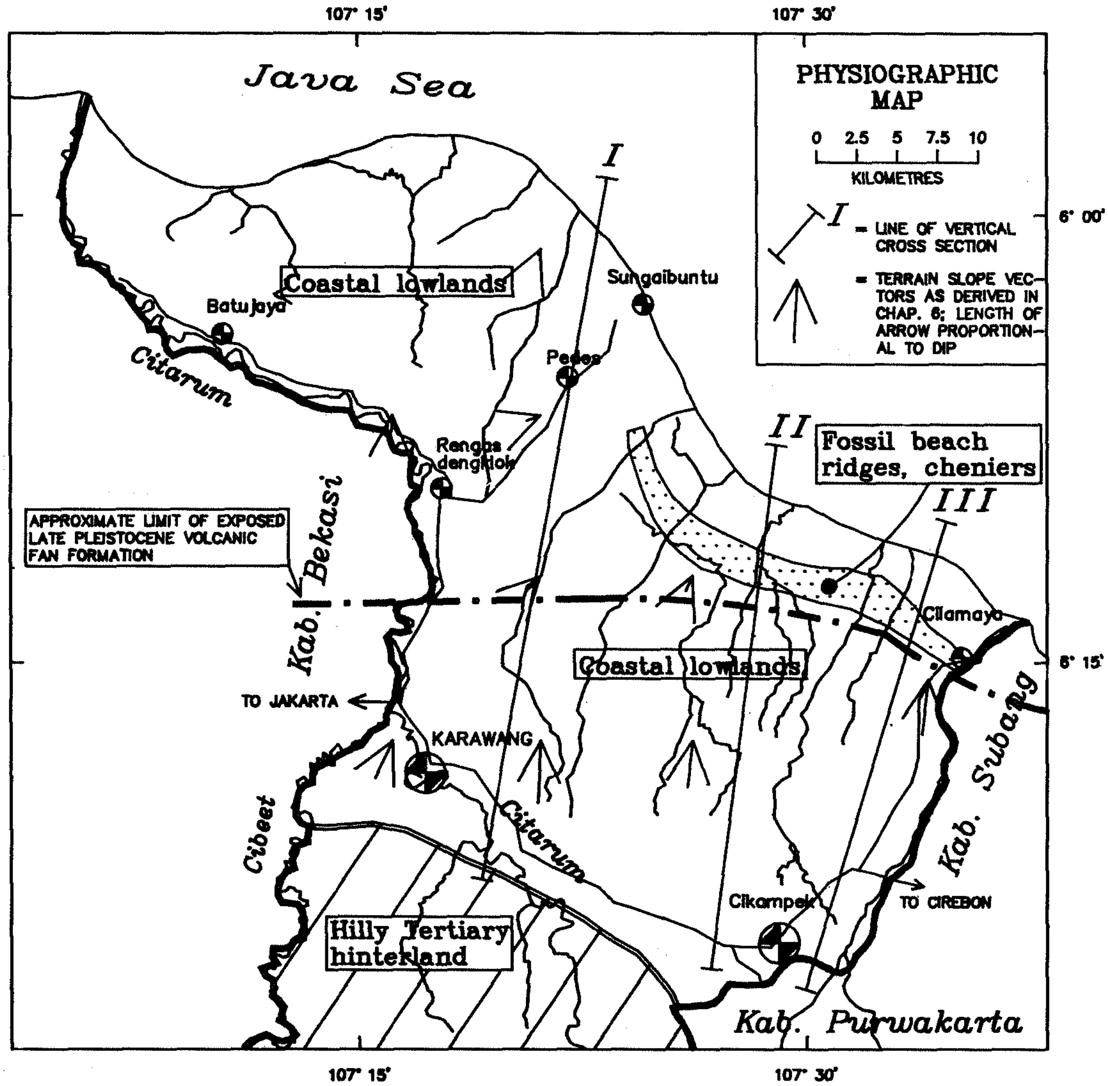


Fig. 7.3 General physical setting of kabupaten Karawang.

Further to the south lies the Plio-Pleistocene (age uncertain might be of the same age as Kromong volcanic complex in kabupaten Cirebon) intrusive complex of the Sanggabuana massif. The summit of this intrusive complex reaches an altitude of 1,291 m and is the highest point on the administrative kabupaten boundary.

The coastal lowlands are situated roughly north of the main road Jakarta-Karawang-Cirebon. The deposits of the lowlands consist of a typical sequence of shallow marine and near-shore deposits to fluviatile clays and silts of the poorly drained flood plain basin of the river Cimanuk. This Holocene series is deposited on top of the Late Pleistocene Volcanic Fan Formation with a decapitated lateritic soil profile. The limit of the exposed part of the sequence of Late Pleistocene volcanic fans is indicated in Fig. 7.3. North of this line the Volcanic Fan Formation becomes fully covered by Holocene deposits. On the other side of the line the Late Pleistocene Volcanic Fan Formation is easily recognized by its characteristic red colour of the remaining soil. Thin veneers of flood plain clays with incipient grey-coloured soils are found only in the broader valleys originating from Holocene dissection.

The courses of the rivers traversing the exposed parts of the Volcanic Fan Formation are fairly straight and flow in a typical NNE direction, as shown by the Citarum and Cilamaya. The presence of the Late Pleistocene Volcanic Fan Formation is not only expressed in the fairly constant river course direction, but also in the position of the Holocene deltas and the parallel rows of fossil beach ridges and shore bars. Holocene delta building could take place only north of the theoretical zero height contour in the erosion surface on top of the substratum. The apex of the Citarum delta appears to be located around Rengasdengklok, which coincides with the position of the top of the substratum at about mean sea level during the Holocene epoch.

Remarkable is the secondary surface drainage pattern in the coastal lowland areas, discharging the flood waters from the river Cimanuk. Before 1925 most of the coastal lowland areas were covered with mangrove swamps along the coast and with extensive back swamps on the flood plain (Bakhoven, 1936). Many village names with the preposition 'Rawa' are still reminders of former marshy conditions. At present the entire area is utilized for intensive irrigated cultivation of rice. Irrigation water is taken in from the rivers Citarum and Cilamaya and distributed by a dense network of canals.

A typical feature of these coastal lowlands is the location of villages and dwelling places on top of former river levees, channel sands and low relief beach ridges and cheniers. Village patterns particularly in the area west of the town of Cilamaya reflect a series of parallel cheniers.

7.4.2 General groundwater setting

A major E-W line can be drawn through the kabupaten slightly north of the town Karawang, dividing the kabupaten into an area in the south with water supply by shallow wells and northern areas where shallow groundwater resources are unfit for human consumption. This fairly sharp groundwater quality dividing line runs roughly parallel to the southern boundary of the Holocene coastal lowland deposits. Shallow wells in the Late Pleistocene Volcanic Fan Formation exposed on the southern side of this major dividing line tap fresh groundwater resources, whereas immediately adjacent wells in the Holocene flood plain clays yield mostly saline waters unfit for human consumption.

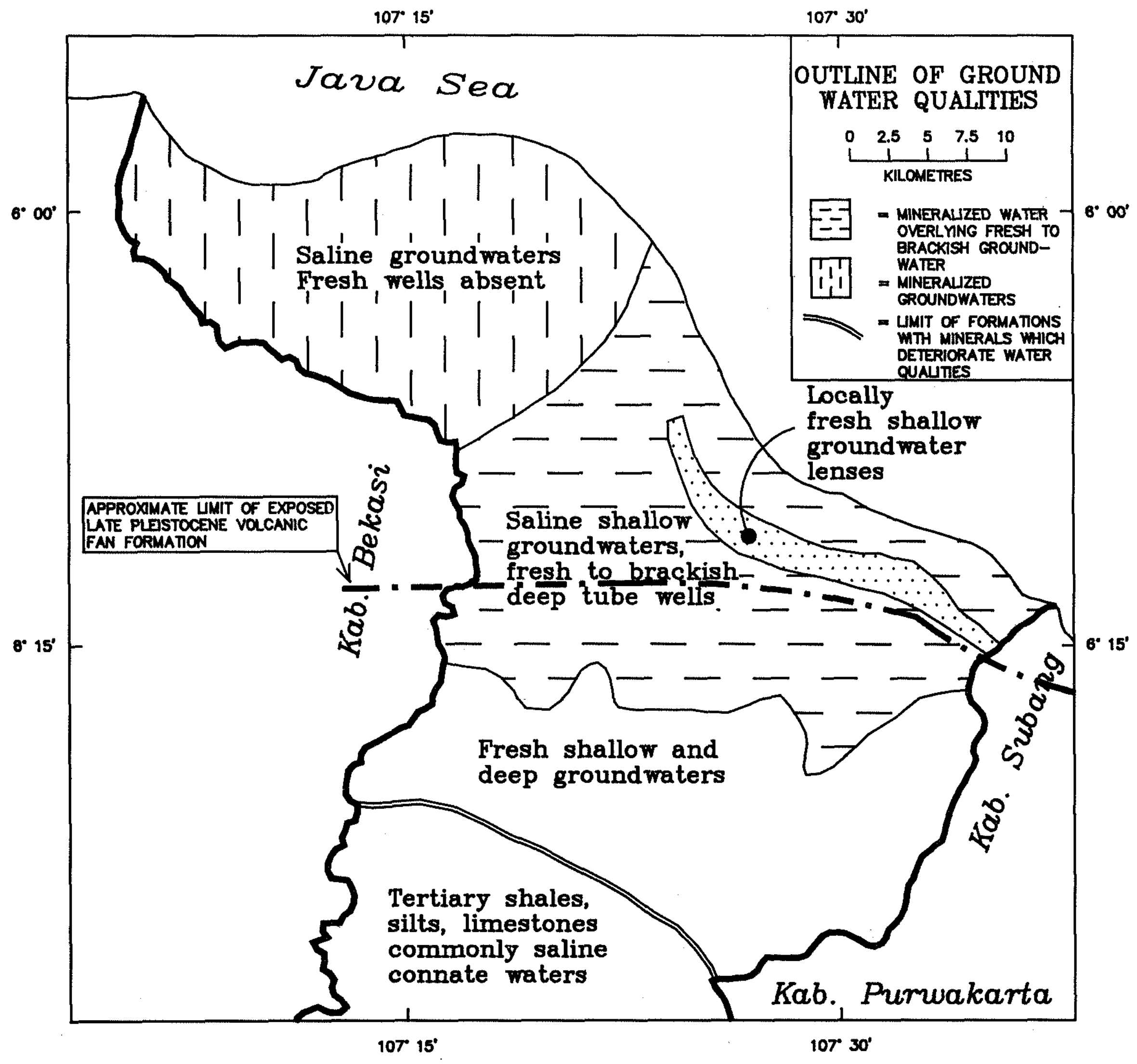


Fig. 7.4 Division of kabupaten Karawang into major groundwater provinces.

This explains the peculiar zigzag shape of the dividing line, caused by broad valleys (cluster 2 in the slope vector analysis of the coastal lowlands; see Chapter VI) in the Volcanic Fan Formation filled with flood plain clays. Slightly deeper dug wells or tube wells reaching the underlying fan deposits may yield groundwater of better quality.

The high salinity of shallow groundwaters in Holocene flood plain clays and silts is a remarkable feature of the coastal lowlands in northern Java. This feature is omnipresent and electrical conductivity values for these shallow groundwaters vary between 2,500 and 10,000 μmhos/cm. It must be emphasized that these salinities are highly variable, are found in groundwaters far from the present-day coast and are unrelated to sea water intrusion. The groundwaters are released from the fluvial clay deposits and apparently not from underlying marine strata, as clearly evidenced by the broad valleys eroded in the fan deposits. Most reports on the groundwater situation in the coastal lowlands do not recognize this peculiar presence of saline groundwaters in fluvial flood plain clays. It follows that domestic water supply from shallow groundwater in the Holocene deposits of fluvial flood plain clays and underlying marine deposits is seriously handicapped by problems of high salinity.

North of the major dividing line, apart from the irrigation canals, domestic water supply can be obtained only from deeper tube wells reaching one of the three regional aquifer horizons (see Chapter V) at depths of more than 45 m. It is a common feature of the newly drilled tube wells to be self-flowing for a few months or even a few years. However, all the owners of these initially artesian tube wells reported declining yields as a function of time and finally hand pumps have to be installed. Yields from tube wells with nominal pipe diameters of 25 to 50 mm are generally much less than 0.5 l/s.

A belt of Holocene cheniers and low beach ridges stretches from the town of Cilamaya in a WNW direction almost parallel to the coastline before it turns to the north and disappears. Small local fresh to brackish groundwater lenses are present in these sand bodies which rest on marine and near-shore deposits.

Approaching the present-day delta of the river Citarum a second groundwater quality divide line is present, beyond which fresh groundwaters are absent.

7.4.3 *Hydrochemical cross sections through kabupaten Karawang*

Three N-S cross sections have been constructed through the kabupaten Karawang based on the well survey data and chemical analyses. The location of the section lines is indicated in Fig. 7.3. A general legend explaining the hydrochemical facies symbols in the cross sections to follow is shown in Fig. 7.5.

Cross section I (see Fig. 7.6) runs from the hinterland with exposed Late Pliocene rocks to the newly accreted delta near Pedes. Fig. 7.6 also depicts the three depth zones in which the clusters of tube wells are found, as derived in Chapter V. Most of the tube well ends appear to fit remarkably well into this framework of three major zones with permeabilities higher than the surrounding strata. Towards the southern part of the sections, thus approaching the strongly deformed belt between the hinterlands and the coastal lowlands, the vertical depth positions of the tube well ends generally become uncertain and are highly conjectural in the sections. The deeper horizons of the geological stratification shown in the section are based mainly on good quality data from two deep water wells drilled under the supervision of IWACO in kabupaten Subang.

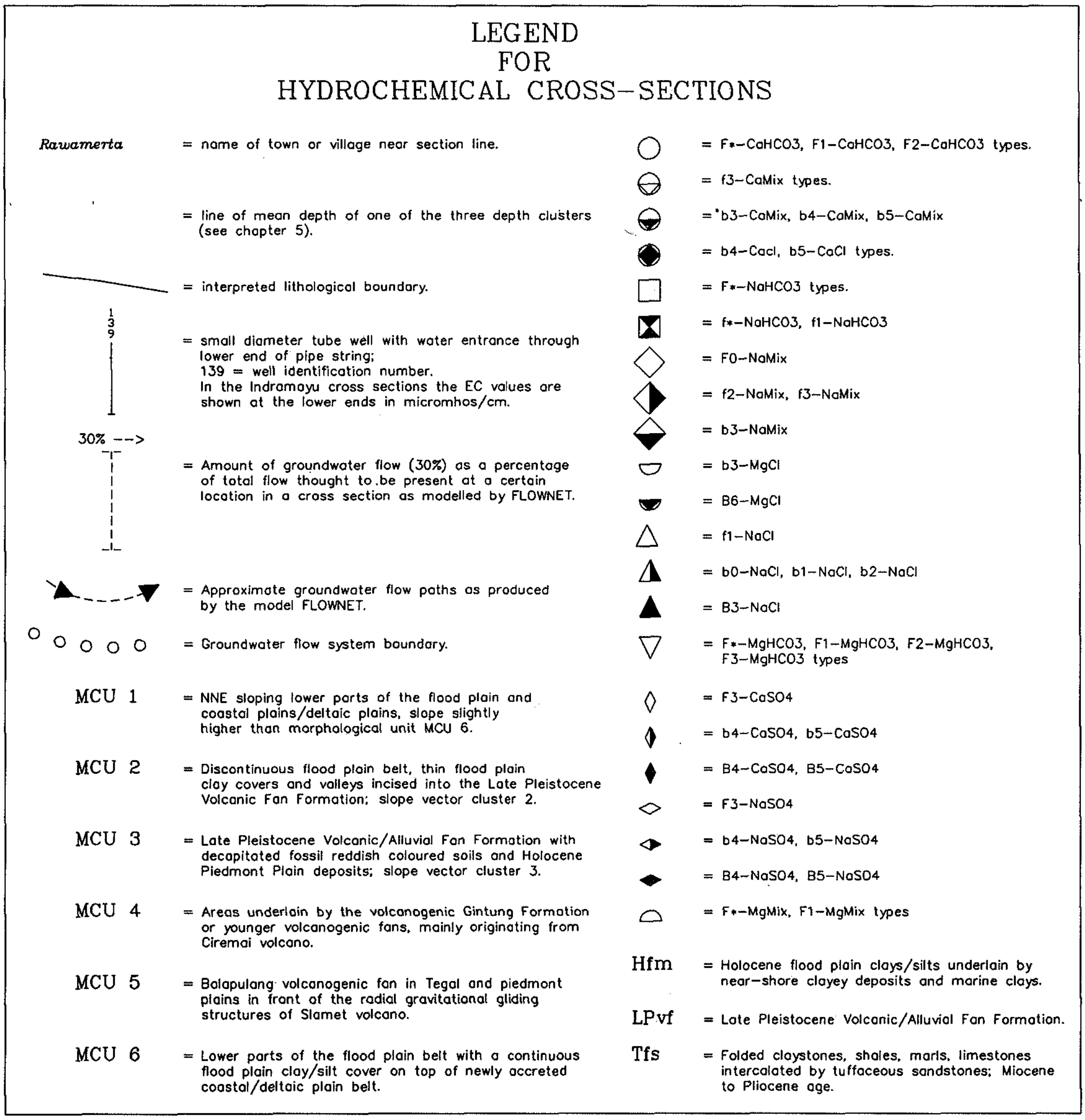


Fig. 7.5 **General legend for the hydrochemical cross sections.**

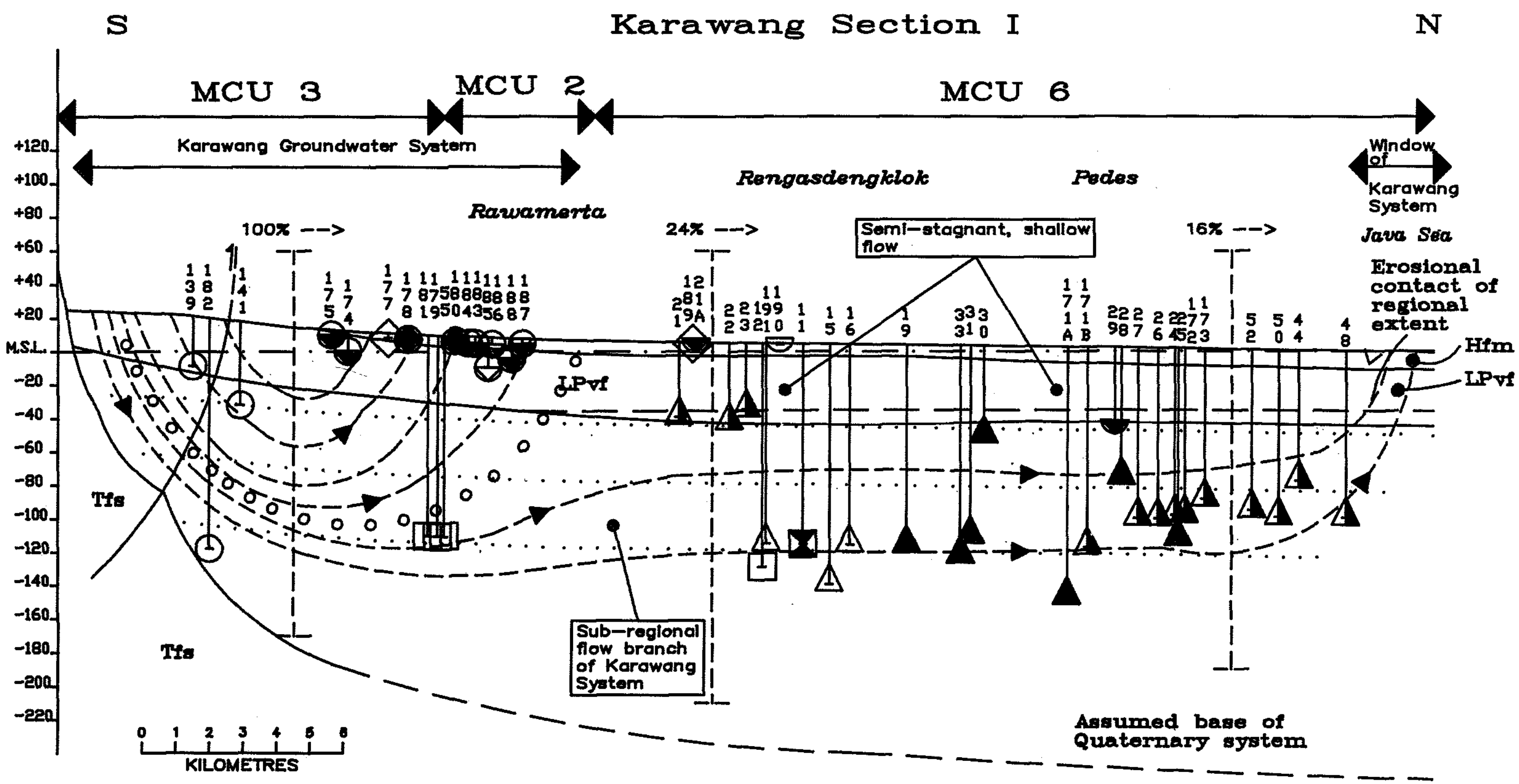


Fig. 7.6 Hydrochemical cross section Karawang I (see Fig 7.5 for general legend).

The bottom of the Late Pleistocene Volcanic Fan Formation is expected to be situated at a depth of about 40 m, overlying an erosional contact of regional extent and partly separated from it by flood plain clays. At the top of the Late Pleistocene volcanic fans another erosional contact is found, overlain by Holocene marine clays and flood plain deposits. This sequence accords with the stratification model outlined in Chapter VI. From this Karawang section I, the impression is gained of a similarity in depth between erosional hiatuses and clusters of tube well end depths. The coastal lowlands shown in this section can be divided into three physiographical zones as derived from the statistical analyses on terrain slope vectors. In the southern part, belonging to slope vector cluster 3, the Late Pleistocene Volcanic Fans Formation is exposed with decapitated reddish soil profiles.

Table 7.1 Examples of the main chemical types of groundwaters in the area of slope vector cluster 3, Karawang I.

Id. Nr.	Depth (m)	EC μmhos/cm	pH	Chemical type
139	30.0	450	6.2	F1-$CaHCO_3$0
141	50.0	680	6.3	F2-$CaHCO_3$+
174	12.0	1,500	7.1	f3-CaMix +
175	3.0	1,500	7.4	f3-CaMix +
182	138.0	560	8.0	F2-$CaHCO_3$+

Shallow groundwaters are poorly mineralized and can be classified as $CaHCO_3$ and CaMix types with some tendencies to NaMix types. The deeper groundwaters appear to be of the same hydrochemical type. Table 7.1 summarizes the main characteristics of groundwater chemistry in the area of slope vector cluster 3.

Closer to the flood plain belt the shallow groundwater quality changes abruptly, especially in the relatively broad valleys of some tens of metres width in which the valley floors are blanketed by flood plain clays. A valley traverse from the very low relief interfluves developed on the Late Pleistocene Volcanic Fan Formation to the stiff flood plain clays and silts gives a transition from low mineralized and acid $CaHCO_3$ type groundwaters (EC values around 500 μmhos/cm) to groundwaters with electrical conductivity values ranging from 2,000 to almost 10,000 μmhos/cm. Even the deeper tube wells tapping groundwater from the underlying substratum have increased electrical conductivities beneath the blanket of flood plain deposits. Table 7.2 lists the hydrochemical types derived for groundwaters in the flood plain clays and silts.

It should be emphasized that the Holocene transgressions on Java reached maxima of only 4 to 6 m above present sea level, whereas the highly mineralized groundwaters in the flood plain clays and silts are at present found at altitudes of about 20 m near Rawamerta. Obviously the source of chloride for the brackish groundwaters cannot be found in the present-day sea. Although a general trend of increasing chloride can be noticed in a seaward direction in the deeper layers, high chloride contents are generally lacking.

Table 7.2 Examples of the main chemical types of groundwater in the flood plain clays and silts in the area of morphological unit 3, Karawang I.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
177	3.0	2,100	7.5	f2-NaMix +
178	3.0	3,800	7.0	b4-CaCl 0
180	3.0	6,900	7.1	B5-CaCl 0
183	4.0	1,750	6.6	f3-CaMix 0
184	4.0	1,800	6.5	b3-CaMix 0
185	18.0	1,600	6.9	f3-CaMix +
186	4.0	1,100	7.0	f3-CaMix 0
187	3.0	2,000	6.4	b4-CaMix 0
188	12.0	4,500	7.9	b5-CaMix +
189	1.0	2,250	7.0	b3-NaMix +
190	1.0	1,800	7.5	f3-MgMix +

Tube well 48 near the present-day coast withdraws groundwater from a depth of 90 m and still has an electrical conductivity of only 2,800 µmhos/cm and a Cl content of 734 mg/l. Similar values were recorded for neighbouring deep tube wells. The pattern of hydrochemical types appears to follow the division into slope vector clusters. Poorly mineralized $CaHCO_3$ and $NaHCO_3$ types are found in the areas of slope vector clusters 2 and 3. NaCl types are mainly found under the low-sloping flood plain belt and newly accreted deltaic plain belt.

A selection of the deeper tube wells and their hydrochemistry is shown in Table 7.3. Three subtypes are found in the deeper aquifer zones; a low hardness $NaHCO_3$ type with relatively high pH values and two NaCl types which differ in hardness and pH value. Although the water is unfit for human consumption, the EC values from the deeper tube wells along this section are still much less than for pure sea water. These chemical types in the deeper layers beneath morphological units 2 and 6 all belong to the typical desalinization series which ideally consists of water passing through the following stages: S-NaCl+, B-NaCl+, B-$NaHCO_3$+, F-$NaHCO_3$+, F-$MgHCO_3$+, F-$CaHCO_3$+ and eventually F-$CaHCO_3$0. Thus one may conclude that the layers, originally containing saline water, are being (or once were) flushed by fresh groundwater. The majority of the chemical types have the + or 0 at the end, indicating fresh water flushing.

As mentioned in the introduction the two-dimensional steady state groundwater flow model FLOWNET has been applied to determine possible flow paths in cross section Karawang I.

Table 7.3 Examples of the main chemical types of groundwater from deeper tube wells in section Karawang I.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
16	120.0	1,400	8.2	f*-NaCl
19	120.0	2,100	7.9	b0-NaCl 0
21	45.0	1,450	7.7	b1-NaCl 0
22	48.0	1,400	7.8	b2-NaCl
31	114.0	3,700	7.8	b2-NaCl
48	90.0	2,800	7.5	b1-NaCl 0
52	96.0	3,400	7.7	b2-NaCl 0
55	120.0	580	8.4	F*-$NaHCO_3$+
171B	120.0	2,200	7.7	b1-NaCl 0
179	120.0	620	8.7	F*-$NaHCO_3$+
181	120.0	650	8.7	F*-$NaHCO_3$+

The main objective of the model application is to find a relationship between the hydrochemical types and expected groundwater flow paths. A major obstacle however, is determination of the subsoil hydraulic parameters. Soefner et al. (1986) applied a vertical, two-dimensional groundwater flow model to the greater Jakarta area from which some parameters are adopted, supplemented by soil permeability tests conducted in the kabupatens Karawang and Indramayu.

Table 7.4 Summary of soil permeability tests in the kabupatens Karawang and Indramayu.

Location	Kabupaten	Lithology	Conductivity m/day
Pedes	Karawang	Silty clays	0.3
Batujaya	Karawang	Flood plain clays	0.2
Dadap	Indramayu	Flood plain clays	0.07
Jatitujuh	Indramayu	Late Pleist. Volcanic Fan	1.2
Limbangan	Indramayu	Sandy fluvial clays	0.15
Suka-urip	Indramayu	Channel sands	2.0
Limbangan	Indramayu	Beach sands	7.4

Fig. 7.7 shows the geohydrological schematization for cross section Karawang I, based on the interpreted geology, the statistically derived depths of the higher permeable zones and the hydraulic conductivities as given by Table 7.4. The horizontal and vertical hydraulic conductivities of the clayey strata of the rigid model, ignoring effects of clay layer compaction, are assumed to be 0.5 and 0.005 m/d respectively. It is further assumed that the conductivities of the clayey strata are further reduced to 0.1/0.001 m/d (K_h/K_v) at depths of more than 150 m (Hinch in Roberts & Cordell (ed.), 1980). The applied hydraulic head at the upper open side of the model is taken to be equal to the topographic altitude, with the sea level as zero level. As will become apparent below the geological structures in the Quaternary basins, including a brackish to salt NaCl groundwater type, continue under the present Java Sea.

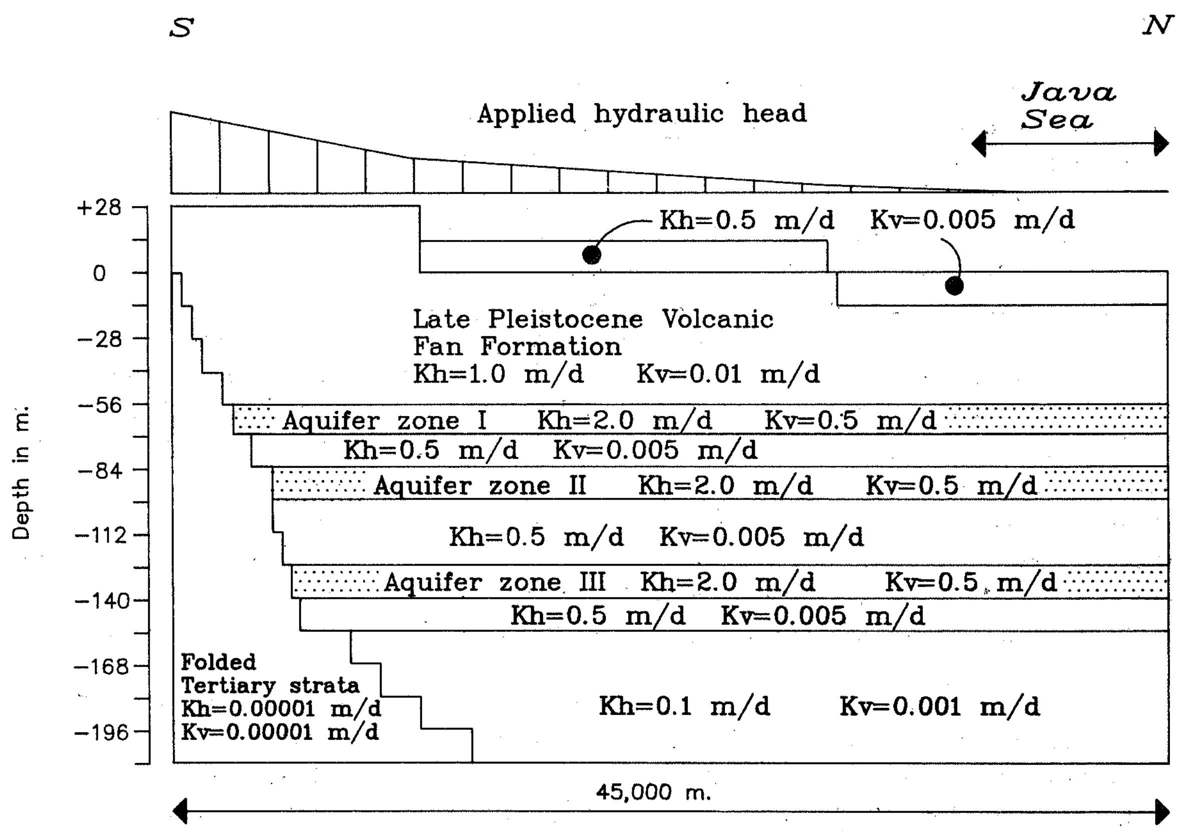


Fig. 7.7 Geometric and hydraulic input parameters, representing cross section Karawang I, for the vertical groundwater model FLOWNET (K_h = horizontal hydraulic conductivity, K_v = vertical hydraulic conductivity).

It implies that in a vertical model the very shallow Java Sea constitutes a thin layer of only a few metres seawater in the top of the model overlying the Quaternary sediments, hence the flow domain is thought to contain groundwater salinities which are well under those for seawater. A number of streamlines of the FLOWNET output are drawn in the cross section of Fig. 7.6. The eye-catching feature of the pattern of streamlines is that groundwater flow is mainly restricted to those parts of the section which lie under the morphological coastal lowland unit (MCU) 3, which consists of the exposed part of the Late Pleistocene Volcanic Fan Formation. The topographic slope on unit 3 is much steeper (1.35 m/km) than that for unit 2 (0.35 m/km along this section) and the abrupt change of slope between the two units apparently generates a local groundwater flow system. Further to the north, slightly beyond flood plain belt unit 2 the remaining groundwater flux is reduced to about 24%. The total flux of groundwater, determined at the point where the descending streamlines are converted to ascending lines, amounts for this particular cross section to only 0.28 m^2/d. Under the newly accreted coastal and deltaic plain the flux is further reduced to only 16%. Thus at the boundary between units 3 and 2 approximately 70% of the total groundwater flux has returned to the surface and become runoff. The topographic slopes of units 2 and 6 (average of 0.27 m/km in unit 6) are too small to secure a significant groundwater flow. Running the model with the hydraulic parameters shown in Fig. 7.7, which are certainly conjectural, the stream lines follow the three zones of higher permeability in which most tube wells ends are found. This may explain the high contrast in water qualities which are often reported by local water well drillers[1].

This pattern of streamlines, in particular the concentration of flow beneath morphological unit 3 leading to the Karawang Groundwater Flow System of the Late Pleistocene Volcanic Fan Formation with a strong short local ascending branch and a weak deeper and longer (sub)-flow branch, accords well with the pattern of groundwater hydrochemistry. It is obvious that the fresh $CaHCO_3$ and $NaHCO_3$ chemical types of groundwater are found in the flow system under unit 3. Although all chemical types of the deeper groundwaters under morphological units 2 and 6 indicate desalinization by flushing with fresh groundwater the final stages in chemical type have obviously not yet been reached, whereas this flushing process is more or less complete for the layers beneath unit 3. This feature seems to accord well with the reduced groundwater flux beyond unit 3. Modelling the cross section of Karawang I further reveals that the residence times for flow paths under units 2 and 6 are hundreds to thousands of years (if the model is correct in this aspect) if effective porosities of 5% in the clayey strata and about 10% in the more sandy intercalations are assumed.

The total groundwater flux entering the model is 0.28 m^2/d for a unit aquifer width of one metre, equal to a discharge of about 3.2 l/s per kilometer aquifer width. Groundwater circulation through the cross section from south to north can be considered as very sluggish, due to the low hydraulic conductivities and gradients available in the coastal lowlands.

1 Local well drillers using low-technology jetting methods to drive tube wells in the subsoil always report a chaotic succession of salt, brackish and fresh groundwaters penetrated during drilling. Tube wells which initially yield salt water can often be 'treated' by pulling the entire pipe string only 1.5 m (1/4 standard pipe length).

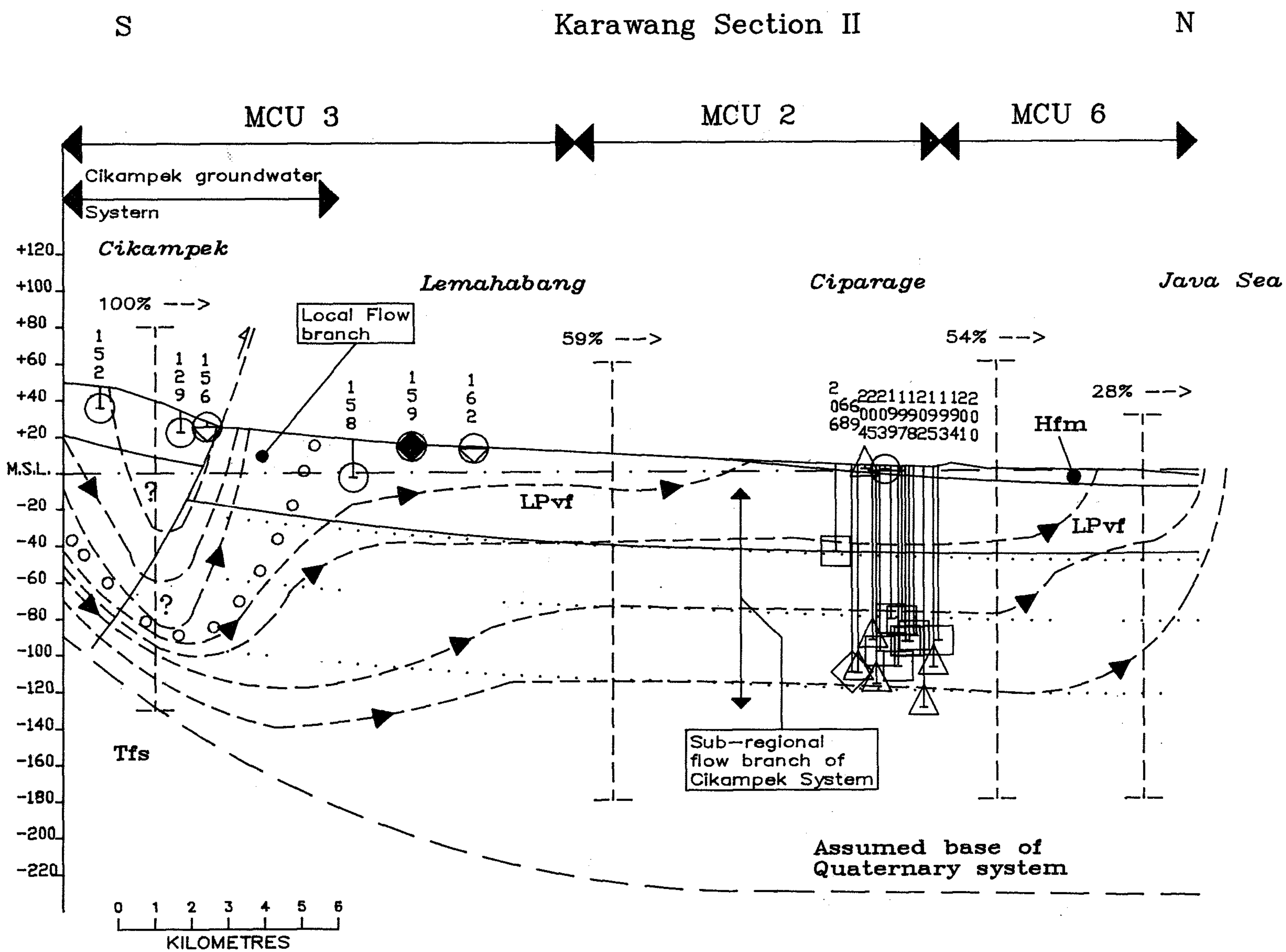


Fig. 7.8 Hydrochemical cross section Karawang II (see Fig. 7.5 for general legend).

Circulation in the longer flow branch is insignificant[2] when compared to the potential recharge by precipitation. In contrast to cross section Karawang I with its broad flat coastal plain/deltaic plain belt is cross section II through Karawang, in which the exposed Late Pleistocene Volcanic Fan Formation dominates the lowland morphology. The coastal plain/deltaic plain belt, morphological unit 6, is comparatively narrow and the Volcanic Fan Formation is present at shallow depths in the subsoil almost to the village of Ciparage. The flood plain belt of morphological unit 2 exhibits a discontinuous cover of thin flood plain clays and silts present only in the broader valleys. Thus it follows that the majority of terrain slopes in this cross section show the typical values found for the Late Pleistocene Volcanic Fan Formation. Towards the east the belt of newly accreted coastal and deltaic plains becomes even narrower. The stratigraphic sequence is expected to be similar to that for section I.

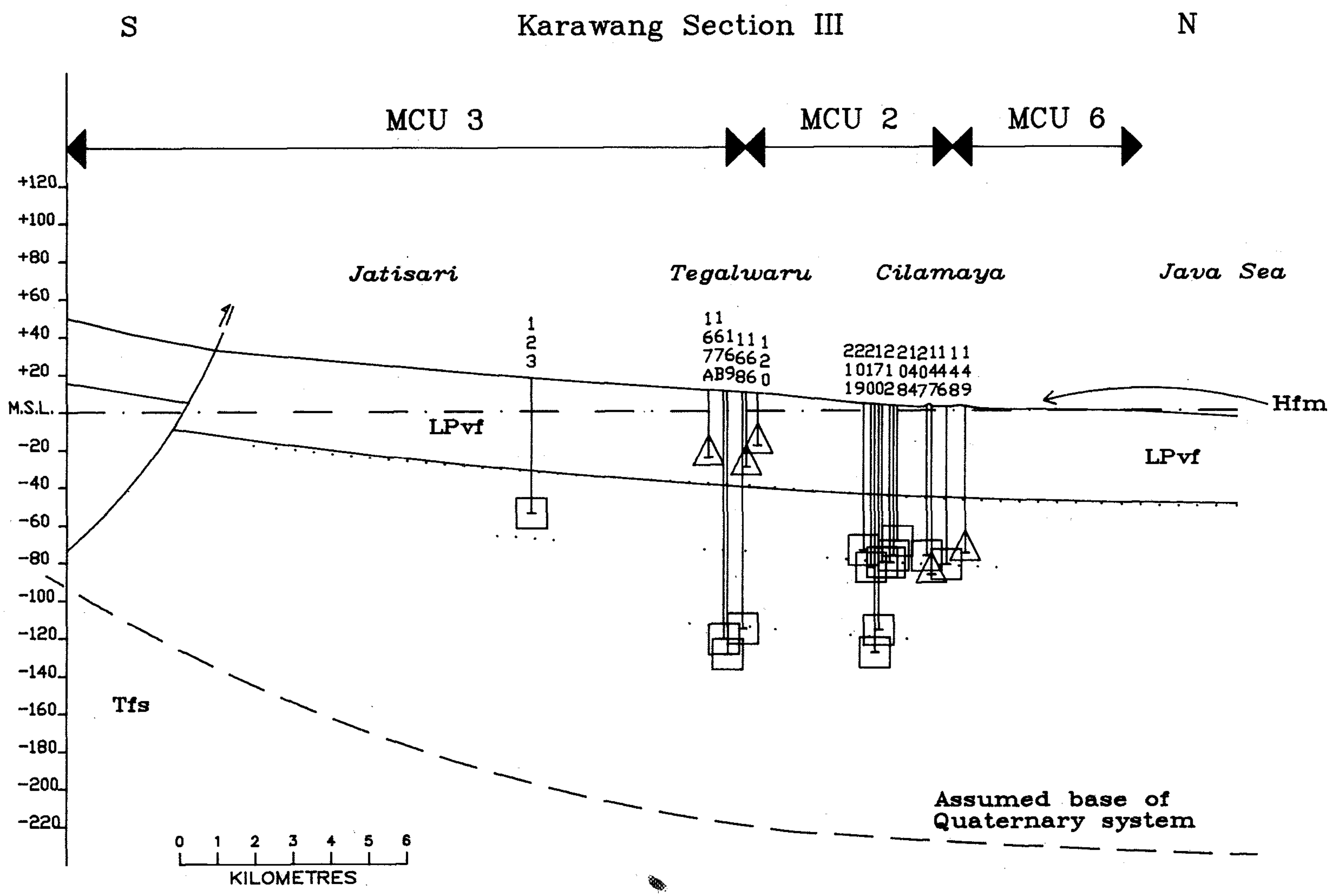
Shallow groundwaters in the Volcanic Fan Formation is mainly of the low mineralized $CaHCO_3$ type. As a result of the good quality shallow groundwaters, deep wells are usually lacking and appear only in the vicinity of Ciparage. Apart from the chenier and beach ridge sands, shallow groundwaters in the flood plain clays and silts are generally unfit for human consumption. Noteworthy in this section II is the good quality for the deeper tube wells near the village Ciparage. This consists mainly of low hardness $NaHCO_3$ types with tendencies towards low mineralized NaCl types with similar relatively high pH values (see Table 7.5). The deeper groundwater situation differs significantly from cross section Karawang I.

Table 7.5 Examples of the main chemical types of groundwater from section Karawang II.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
68	114.0	800	8.1	F0-NaMix +
152	12.0	350	6.3	F1-CaHCO3O
156	2.5	100	5.5	F0-CaMix 0
158	21.0	300	6.7	F1-CaHCO3+
162	1.0	850	6.1	F2-CaMix +
194	132.0	1,100	8.6	f*-NaCl
199	102.0	690	8.7	F*-NaHCO3+
200	96.0	670	8.1	F*-NaHCO3+
201	110.0	850	8.7	f0-NaCl
202	85.0	710	8.4	F0-NaHCO3+
206	48.0	570	8.7	F*-NaHCO3+

2 One may assume an average annual precipitation depth of 1,500 mm in the recharge areas with the descending streamlines in cross section Karawang I and further that 300 mm is available for deeper groundwater recharge. In that case a strip of only 340 m width would hypothetically be sufficient to supply the flux of groundwater. In reality the width of strip with descending streamlines is about 7.5 kilometres.

Fig. 7.9 Hydrochemical cross section Karawang III (see Fig. 7.5 for general legend).



The superimposed pattern of streamlines through the aquifer may yield the clues behind the fresh deeper groundwaters. Since the topographic slope is formed by the Volcanic Fan Formation it follows that a steeper hydraulic gradient is available to propel groundwater flow. This can be seen from the cross section flux percentage at the beginning of morphological unit 2 (still 59%), whereas even beyond the village Ciparage with numerous deep tube wells the groundwater flux has decreased to only 54%. These figures are much higher than those in cross section Karawang I. The residence times of water particles travelling through cross section Karawang II are also much shorter. The fresh deeper groundwater situation thus fits very well into the pattern and fluxes of groundwater flow. The contiguous Cikampek Groundwater Flow System which is driven by the central highest part of the relatively steep topography on unit 3, the Late Pleistocene Volcanic Fan Formation, has apparently been capable of flushing the deeper layers much more than the lower western part flushing section I.

Cross section Karawang III resembles Karawang II in that the relief and slope vectors are completely dominated by the Late Pleistocene volcanic fans. Again the flood plain and coastal/deltaic plains are only a few kilometres wide and have a lesser width than in section II. Remarkable is the small cliff developed in the volcanic fan materials near Cilamaya. This cliff extends into the neighbouring kabupaten Subang. It represents the end stage of the Holocene transgression and is similar in genesis to the beach rock deposits found in the hinterland hills in Tegal. It is a well-preserved example of an erosional surface sculptured during a glacial period, which is subsequently transgressed in an inter-glacial period to a limit determined by the maximum attained sea level. Except for the shallow groundwaters in the flood plain clays and silts and the newly accreted coastal plain on the marine and near-shore deposits, the groundwater situation does not pose serious problems. Electrical conductivity values of the well waters from all the deeper tube wells surveyed in 1982 are well under 1,000 μmhos/cm. As expected, the dominating chemical type is the low hardness $NaHCO_3$ type with high pH values, though some wells belong to the low mineralized NaCl type with slightly lower pH. For the sake of completeness a selection of tube wells and their hydrochemical types is shown in Table 7.6. Cross section Karawang III resembles Karawang II in hydrochemistry of the deeper groundwaters and the dominant role of unit 3 in the morphology. A pattern of groundwater flow similar to that derived for Karawang II is thus expected for this section.

Table 7.6 Examples of the main chemical types of groundwater from section Karawang III.

Id. Nr.	Depth (m)	EC μmhos/cm	pH	Chemical type
120	24.0	800	8.1	f1-NaCl 0
123	72.0	400	8.0	F0-$NaHCO_3$+
149	78.0	600	8.0	F*-NaCl ·
167B	132.0	480	8.5	F*-$NaHCO_3$+
169	140.0	480	8.8	F*-$NaHCO_3$+
210	132.0	550	8.4	F0-$NaHCO_3$+
211	78.0	480	8.3	F*-$NaHCO_3$+

7.4.4 *Conclusions on the groundwater hydrochemistry in kabupaten Karawang*

Having described the three cross sections through kabupaten Karawang, the following conclusions can now be drawn:

1) in general the last parameter of the hydrochemical types (see also Appendix II), i.e. the sum of Na, K and Mg in meq./l corrected for sea salt, points to an equilibrium for the deep tube wells with NaCl type well waters and to a surplus for the $NaHCO_3$ groundwater types, suggesting flushing by fresh groundwater;
2) all the chemical types of the deeper groundwaters belong to a typical desalinization series;
3) none of the surveyed deeper tube wells, even in the northwestern part of the kabupaten, yielded groundwaters with salinities comparable to those of sea water;
4) low mineralized $CaHCO_3$ types of groundwater are found in the exposed parts of the Late Pleistocene volcanic fans. Shallow groundwaters in the fan deposits overlain by flood plain material have chemical types resembling those of the flood plain clays;
5) shallow groundwaters in the fine-grained Holocene flood plain deposits are strongly mineralized and exhibit varying qualities at the scale of an outcrop;
6) a major consistent groundwater flow system, the Late Pleistocene Volcanic Fan Formation Flow System, is found beneath morphological unit 3, bounded by Tertiary rocks in the south and the abrupt break in slope between this unit and the Holocene flood plain belts of units 2 and 6;
7) the groundwater flow system under unit 3 has been capable of flushing the original saline pore waters in the deeper layers. The dominant chemical types of the deeper groundwaters are $NaHCO_3$ and $CaHCO_3$;
8) a relation exists between the subdivision into morphological coastal lowland units and the chemical types of groundwaters in the deeper aquifers; via the mechanism of gravity-driven, fresh groundwater flow systems recharged at topographically higher zones, in particular the huge alluvial-volcanogenic fans near Cikampek;
9) there is a good correspondence between the tube well end depths and the statistically derived depth clusters;
10) major groundwater areas which are dominated by the physiographic region of slope vector cluster 3 exhibit fresh deep groundwaters, principally of $NaHCO_3$ type;
11) the more permeable horizons in which most tube wells end have reached a further stage in flushing as compared with the surrounding clayey strata.

7.5 *Kabupaten Subang*

7.5.1 *General physical setting*

The elongated kabupaten Subang in West Java lacks the conspicuous deltas found in the neighbouring kabupaten Karawang. The major rivers traversing the kabupaten Subang have their distal boundaries on the northern slopes of the typical double row of volcanoes found only in West Java.

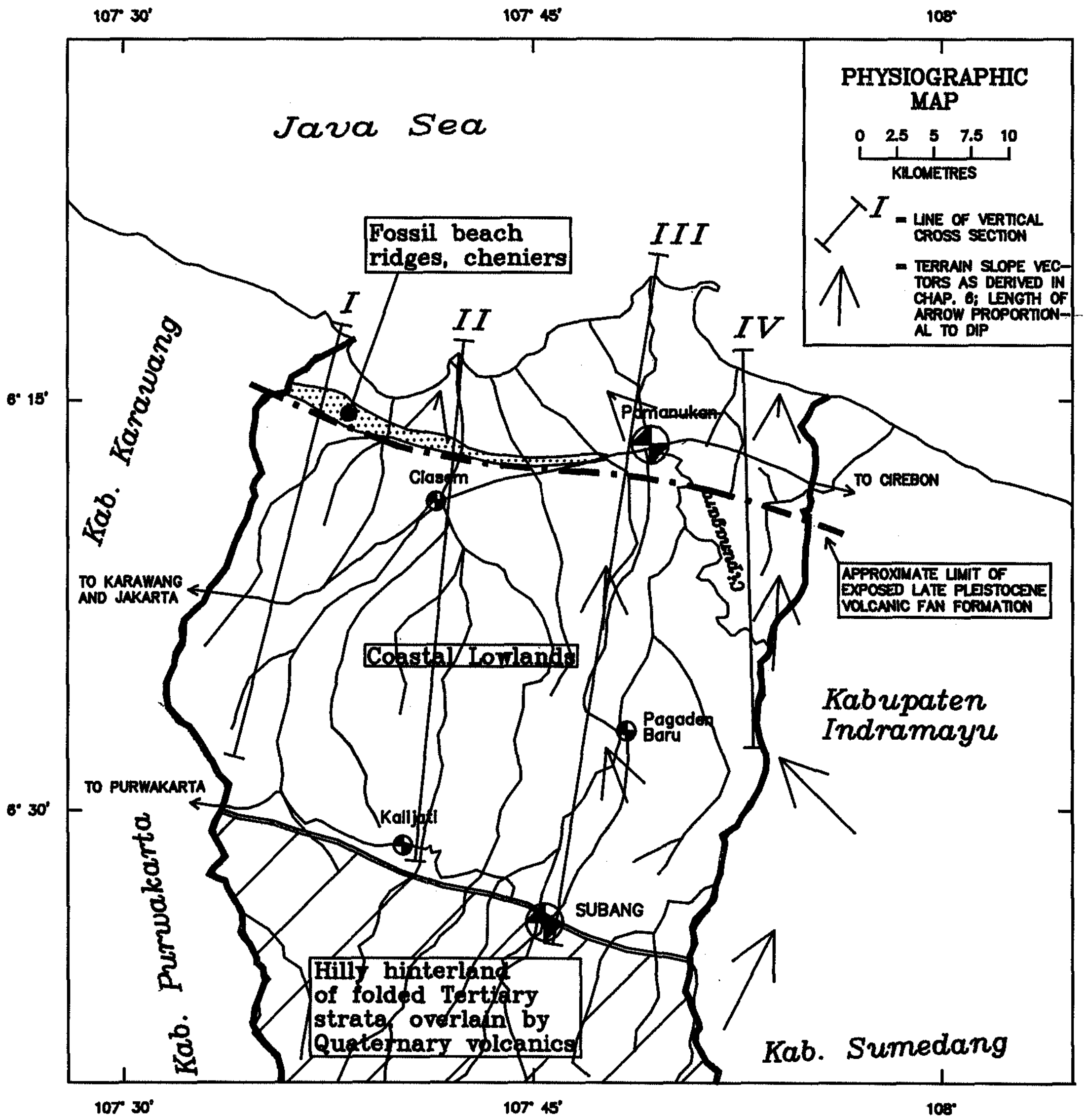


Fig. 7.10 General physical setting in kabupaten Subang.

The river Cipunegara, draining the northeastern and northern slopes of the volcanoes Tangkuban Perahu and Bukittinggi near Bandung, is actively building a small delta north of the town Pamanukan. Watersheds of the remaining streams situated in the hilly Tertiary hinterlands are apparently too small to yield sufficient suspended loads for substantial delta building. The final result is an arcuate shoreline interrupted only by the Cipunegara delta.

From a morphological point of view the elongated kabupaten can be divided into the coastal lowlands and a hilly hinterland consisting of strongly folded, fine-grained rocks, overlain by huge masses of Quaternary volcanics, grading therefore into a mountainous area. The dividing line between coastal lowlands and hinterland is roughly formed by the road from the county town Subang to Purwakarta. The morphological transition from hinterland to coastal lowlands is abrupt, particularly in the area near the town of Subang.

Similar to kabupaten Karawang, the Late Pleistocene Volcanic Fan Formation is exposed over vast areas in the coastal lowlands and is easily recognizable by the typical red coloured soil. The approximate exposure limit of the Fan Formation runs from Cilamaya in kabupaten Karawang in an eastern direction, slightly south of the town Pamanukan, towards kabupaten Indramayu. North of the town Ciasem and south of Pamanukan 8 m high cliff-like steps are found in the topography which are similar to those near Cilamaya in kabupaten Karawang. Large areas of the Fan Formation are veneered by flood plain clays in the vicinities of the larger rivers such as Ciasem and Cipunegara.

As found in kabupaten Karawang, a strong contrast can be noticed between the drainage patterns of rivers flowing on the Pleistocene and older substrata and those on the Holocene coastal plain. The normal dendritic drainage patterns of effluent streams slightly incised into the erosional surface is reversed to a delta-type channel pattern, with a terrain slope away from the main channels and the development of secondary drainage systems in the flood basins. The slope vectors south of Pamanukan also indicate appreciable slopes compared to those in the newly accreted coastal and deltaic plain north of Pamanukan. Near Pamanukan the secondary drainage system on both sides of the river Cipunegara is particularly well developed. Beyond the limit of Late Pleistocene Volcanic Fan Formation exposure, the Cipunegara abruptly changes its direction to a NNW course and the shape of the meanders also seems to have altered. Comparable morphological features are found for the river Ciasem, which changes its channel rapidly from a dendritic erosional type to a depositional deltaic type.

7.5.2 General groundwater setting

Considered at the scale of a kabupaten the groundwater quality situation in kabupaten Subang follows the same pattern as described for kabupaten Karawang. In the southern part the folded Tertiary shales, mudstones, and claystones release highly saline, largely connate groundwaters through small perennial seepages and very small springs. The huge masses of Quaternary volcanics on top of the Tertiary basement contain low to very low mineralized good quality groundwaters, which are discharged through springs, seepages and base flow feeding perennial streams.

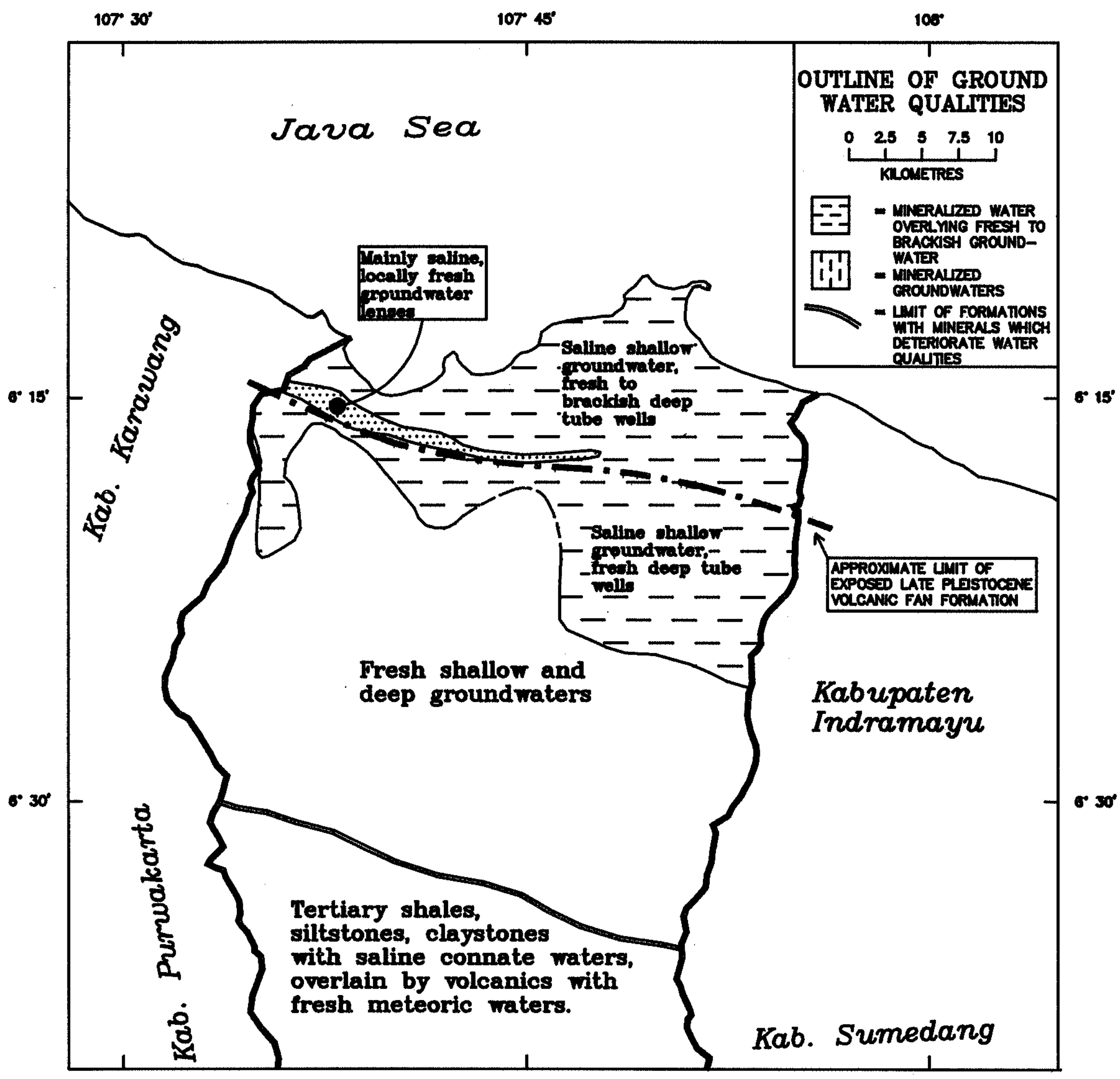


Fig. 7.11 Division of kabupaten Subang into major groundwater provinces.

The southern belt of the coastal lowlands, in which the Late Pleistocene Volcanic Fan Formation is exposed, is characterized by fresh groundwaters at shallow depths and presumably also at deeper levels. Domestic water supplies are generally fetched from regular dug wells and only in those areas with more topographical relief are water levels too deep for suction hand pumps and deep well pumps have to be used.

The major dividing line for groundwater quality runs parallel to the approximate limit of the exposed Late Pleistocene Volcanic Fan Formation. It is the veneer of flood plain clays and muds deposited by the rivers Cipunegara, Ciasem and Cilamaya that deteriorates the shallow groundwater. If the shallow and deeper groundwaters are combined into a single mappable quality unit then the present boundary indicated in Fig. 7.11 is located further to the south. North of this dividing line of groundwater quality are found the saline shallow groundwaters from the belt of Holocene flood plain clays. Mainly fresh groundwater is produced from the numerous deep tube wells south of the exposure limit of the Late Pleistocene Volcanic Fan Formation, with fresh to brackish types beyond this limit. Domestic water supply in the flood plain belt is withdrawn from numerous deep tube wells, tapping one of the three regional zones with higher permeabilities derived statistically in Chapter V. Areas in which even the deeper tube wells produce brackish groundwaters unfit for human consumption or at least not used as drinking water by the local inhabitants, are found in the northeastern parts of the kabupaten.

The cheniers and fossil shore line bars in kabupaten Karawang continue in Subang and can be traced almost to Pamanukan.

7.5.3 Stratigraphic investigations on two deep wells south of the town Pamanukan[3]

Two deep water wells have been drilled in 1982 with the purpose of supplying a piped water supply system to Pamanukan. Rotary drilling rigs were used to drill both wells which reach end depths of slightly more than 150 m. Samples were collected from the circulating drilling fluids at the well collar each time the drill bit penetrated a further metre. One well is located slightly south of the town centre of Pamanukan along the road Pamanukan-Subang, whilst the other well is located along the same road at a distance of 10 km south of Pamanukan.

Geological analysis of the samples was carried out at the National Institute for Geology and Mining (LIPI) at Bandung. Djoehanah (1984) studied the samples and compiled the results on lithology and faunal content. Djoehanah's results have been reinterpreted by the present author in the light of present knowledge of the Holocene build-up of the coastal lowlands. The lithological logs show two important depth zones; an upper one to a depth of 50 m without faunal content and a deeper one with abundant Foraminifera and zones with shell fragments (see Fig. 7.12). This deeper zone of about 100 m thickness is interpreted as being entirely marine and consists of deltaic slope sediments underlain by a subaqueous delta plain.

3 In the framework of the Indonesian-Netherlands development project 'Fifteen cities water supply project' on West Java, two deep wells have been drilled south of the town of Pamanukan. The objective was to investigate the use of groundwater as a source for the piped water supply system of Pamanukan. IWACO conducted both the supervision on well drilling and the supply system implementation.

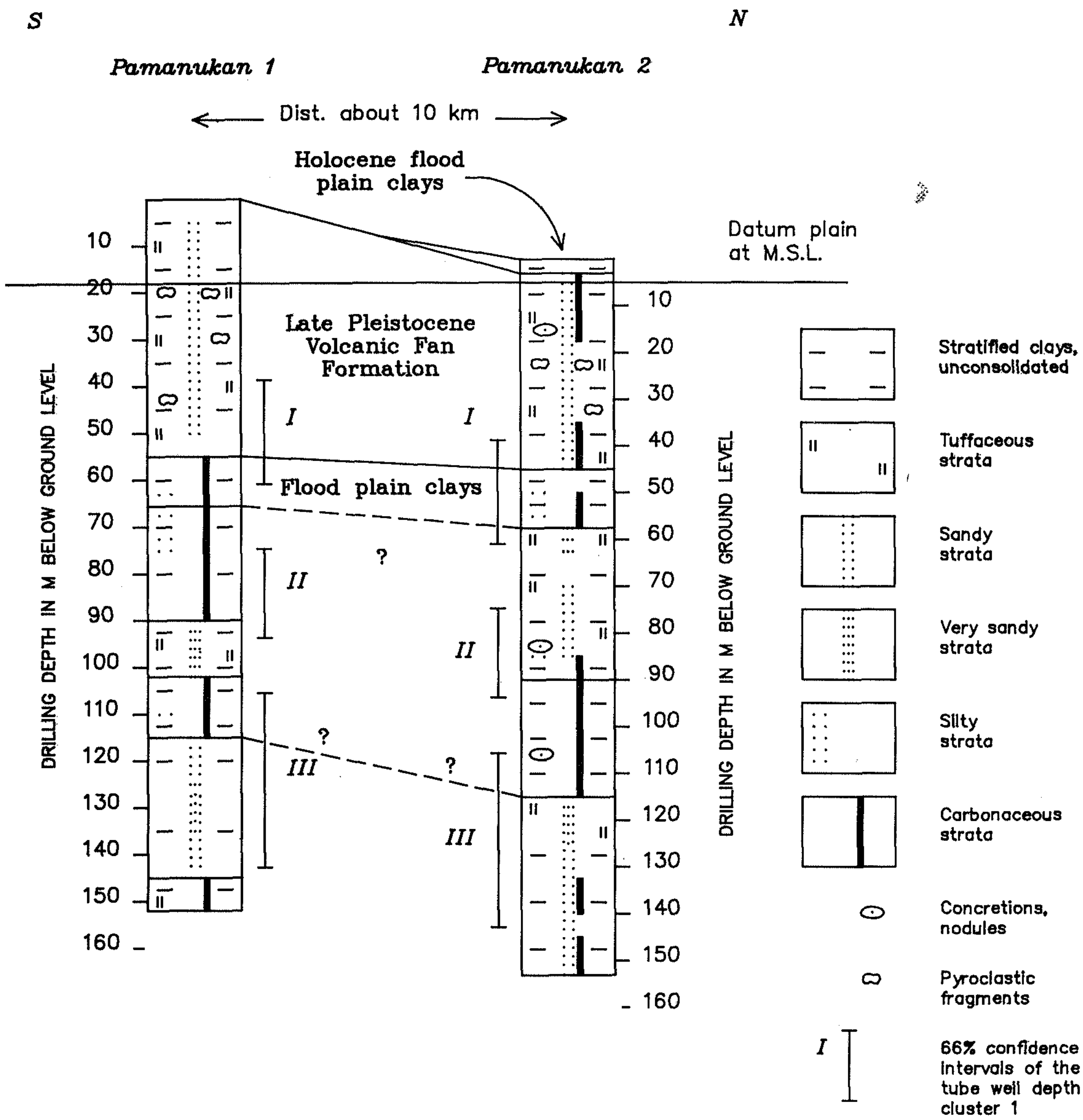


Fig. 7.12 Lithological logs of the deep wells Pamanukan 1, situated about 10 km south of Pamanukan along the road Pamanukan-Subang and Pamanukan 2, near the town itself. Lithology simplified and modified after Djoehanah (1984). The three statistically derived tube well depth clusters are represented as 68% confidence intervals around the mean.

The non-fossiliferous upper zone is considered to be a fluviatile- and volcanic fan. The present author agrees with this interpretation of the upper non-fossiliferous zone, but not with the entirely marine character of the deeper zone. Based on present knowledge of eustatic sea level changes during the Quaternary, accompanied by presumably long glacial periods with strong tendencies for drier climatic conditions, it is difficult to imagine a continuous marine sequence of about 100 m thickness. Even during humid tropical conditions as witnessed today, it follows that typical regressive sequences consist of open shelf marine clays overlain by near-shore deposits and topped by vast fluvial flood plain clays and silts, with occasional beach ridges and coastal swamp deposits. The thickness of the lithological units is generally in the order of a few metres. Judging from the lithological descriptions by Djoehanah the sediments are typical near-shore deposits and in this sedimentary setting the absence of any terrestrial flood plain clays is highly questionable. The interpretation of Djoehanah also runs counter to lithological descriptions by Marks (1956), Soekardi (1972) of deep wells in the Jakarta area and data from offshore core samples in the Sunda shelf area by Geyh & Kudrass (1979) and Biswas (1973), in which the sediment pile is thought to consist of frequent alternations of marine and terrestrial sediments. Their interpretation fits into the sedimentary model of net outward building of coastal lowlands into a very shallow low-energy sea, which is disturbed only by sea level changes, basin tectonics and diagenetic compaction of the predominantly montmorillonitic clayey sediments. The interpretation by Djoehanah of a delta slope is now considered to be erroneous, as it is unlikely that Quaternary sediments have been deposited in much deeper marine conditions than the very shallow ones that prevail today in the Java Sea. In such a very shallow marine environment delta slopes with typical foreset bedding will certainly not develop due to a lack of submarine slope along which slumping takes place. It thus follows that the more sandy parts described by Djoehanah have not been deposited on a delta slope but most likely as beach ridges and shore bars.

The present author is inclined to the opinion that the samples had already been mixed in the hole, as is common with rotary drilling. In addition, one has to take into account the unreliable method of sampling at the well collar by usually unskilled personnel. The highly variable viscosity of poorly prepared drilling fluids and the fluctuations in pumping rates do not promote reliable sampling. This implies that the accuracy due to such sampling methods is much less than suggested by a sampling interval of one metre. Lithological details of a few metres thickness are possibly lost and different formations may come out of the casing completely mixed.

The importance of the lithological descriptions of these Pamanukan deep wells, separated by about 10 km, lies not so much in the recognition of marine and non-marine layers of a few metres thickness but more in the significant thickness of the Late Pleistocene Volcanic Fan Formation. On both well logs this Fan Formation is easy to recognize and is lithologically clearly separated from the underlying formations. Even over a distance of ten kilometres the Volcanic Fan Formation differs only slightly in thickness. The tube wells in depth zone I obviously tap groundwater from the base of the fan which may be coarser grained. The fan is interpreted as lying on flood plain clays. The remaining depth clusters II and III appear to correspond with more sandy formations, particularly cluster III. The length of the 68% confidence interval around the mean for the third cluster, which is larger than the second, seems to be also reflected in the depth interval of the sandy zones from about 115 to 150 m. Due to the unreliable sampling methods at the well collar and the expected lateral changes in lithologies, no attempts have been made to correlate the deeper strata penetrated by the wells. Nevertheless, one might argue that yet another correlation is possible between the sandy zones at depths from 115 to 150 m. This zone appears to be omnipresent and many tube wells withdraw groundwater from it. The total zone thickness of about 35 m is noteworthy, since the Quaternary geology map sheets of the coastal lowlands show beach ridge sands and bars in cross sections to be only 1 to 4 m thick and developed strictly locally. Based on present knowledge of the Holocene geology one may thus conclude that other processes have been responsible for the deposition of these sandy formations.

7.5.4 Hydrochemical cross sections through kabupaten Subang

The kabupaten of Subang was surveyed in 1983 in much greater detail than kabupaten Karawang. This justifies the number of four cross sections. The first section is located in the western part of the kabupaten and is characterized by a very narrow Holocene coastal plain belt. The largest part of the section is occupied by the Late Pleistocene Volcanic Fan Formation, overlain by younger volcanic fan deposits which presumably originate from the Tangkuban Perahu volcano, in the south. The terrain slope changes abruptly just south of well 382 (see Fig. 7.13). The importance of this section is the hydrochemistry of groundwaters in the Late Pleistocene Volcanic Fan Formation. In the southern part very poorly mineralized groundwaters are tapped by the dug wells. Electrical conductivity values are less than 100, with deep water tables of 10 to 15 m below ground level. The chemical types include mainly $CaHCO_3$, $MgHCO_3$ and $NaHCO_3$ types with pH values from 5.0 to 7.0. Interesting is a $NaHCO_3$ type (Id. nr. 359, 360 and 371) which at first glance resembles the chemical type of a desalinization series in the deeper aquifers, but with pH values which are significantly lower.

Table 7.7 Examples of the main chemical types of groundwater from section Subang I.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
250	48.0	560	8.1	F*-$NaHCO_3$+
263	1.0	8,700	7.0	B4-NaCl 0
268	1.0	1,450	7.4	F3-$MgHCO_3$+
283	36.0	330	8.2	F0-$NaHCO_3$+
359	12.0	360	6.5	F0-$NaHCO_3$+
360	18.0	400	6.6	F1-$NaHCO_3$+
371	2.0	140	6.0	F*-$NaHCO_3$+
385	14.0	450	6.8	F3-$CaSO_4$ +
392	12.0	1,800	7.4	F4-$CaSO_4$ +
402	20.0	210	8.0	F*-$NaHCO_3$+

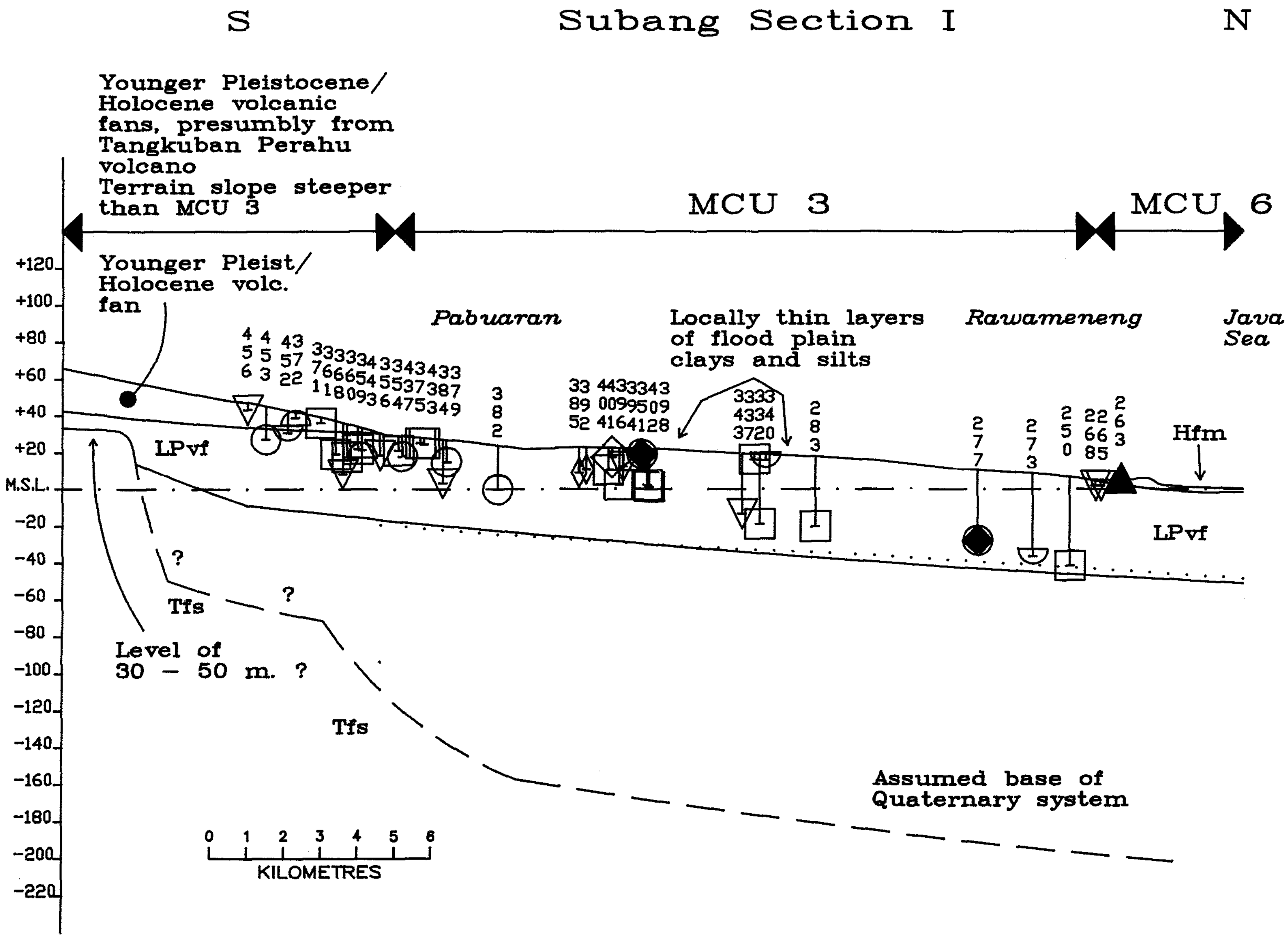


Fig. 7.13 Hydrochemical cross section Subang I (see Fig. 7.5 for general legend).

In this case the Na ions are most likely released by weathering from feldspar minerals in the volcanic materials. The $NaHCO_3$ leaching types of the shallower tube wells show groundwaters with low pH and relatively high hardness indexes, whilst the deeper $NaHCO_3$ exchange types exhibit the reverse pattern of low hardness and high pH. This indicates removal of Ca ions from solution by precipitation or adsorption to clay minerals.

Highly mineralized CaCl and MgCl types are found in the thin cover of Holocene flood plain clays on the Volcanic Fan Formation. Deeper tube wells in the Volcanic Fan Formation still yield poorly mineralized groundwaters. Of interest are the $CaSO_4$ water types from the wells 385 and 392. These are presumably related to the presence of layers of coastal swamp deposits with the characteristic mineral jarosite, as reported by Rimbaman et al. (1986) near Cilamaya. Village medical physicians near Ciasem have reported increased incidences of kidney disease following consumption of from high-sulphate water from dug wells.

Dug wells 265 and 268 withdraw fresh $MgHCO_3$ groundwaters from lenses in fossil beach ridges. Dug well 263 taps salty groundwater from the underlying Holocene nearshore and shallow marine deposits.

The significance of this section is the presence of poorly mineralized groundwaters in the Volcanic Fan Formation both at shallow and deeper levels, if not contaminated by local intercalations of fossil coastal swamp deposits.

The hydrochemical cross section Subang II is remarkable for the occurrence of fresh deep groundwaters near the present-day coast. In this section the Late Pleistocene Volcanic Fan Formation is also the dominant exposed lithological unit. The Holocene coastal and deltaic plain near the river Ciasem is not more than 3 km wide. The majority of deep tube wells, which seem to have their lower ends into one of the regional depth clusters, are characterized by fresh low hardness $NaHCO_3$ types. However, the presence of some fresh to slightly brackish NaCl and Namix types points to inhomogeneities in water quality in the deeper aquifer horizons, probably due to interfingering. This appears to be characteristic for these coastal lowlands.

Table 7.8 Characteristic chemical types of groundwater in the deeper aquifer horizons from section Subang II.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
185	96.0	760	8.0	F*-NaHCO3+
205	141.0	650	8.6	F*-NaHCO3+
212	144.0	620	9.2	F*-NaMix +
217	144.0	1,050	8.5	f*-NaCl
222	102.0	880	8.2	FO-NaHCO3+
415	3.5	80	5.5	F*-NaMix +

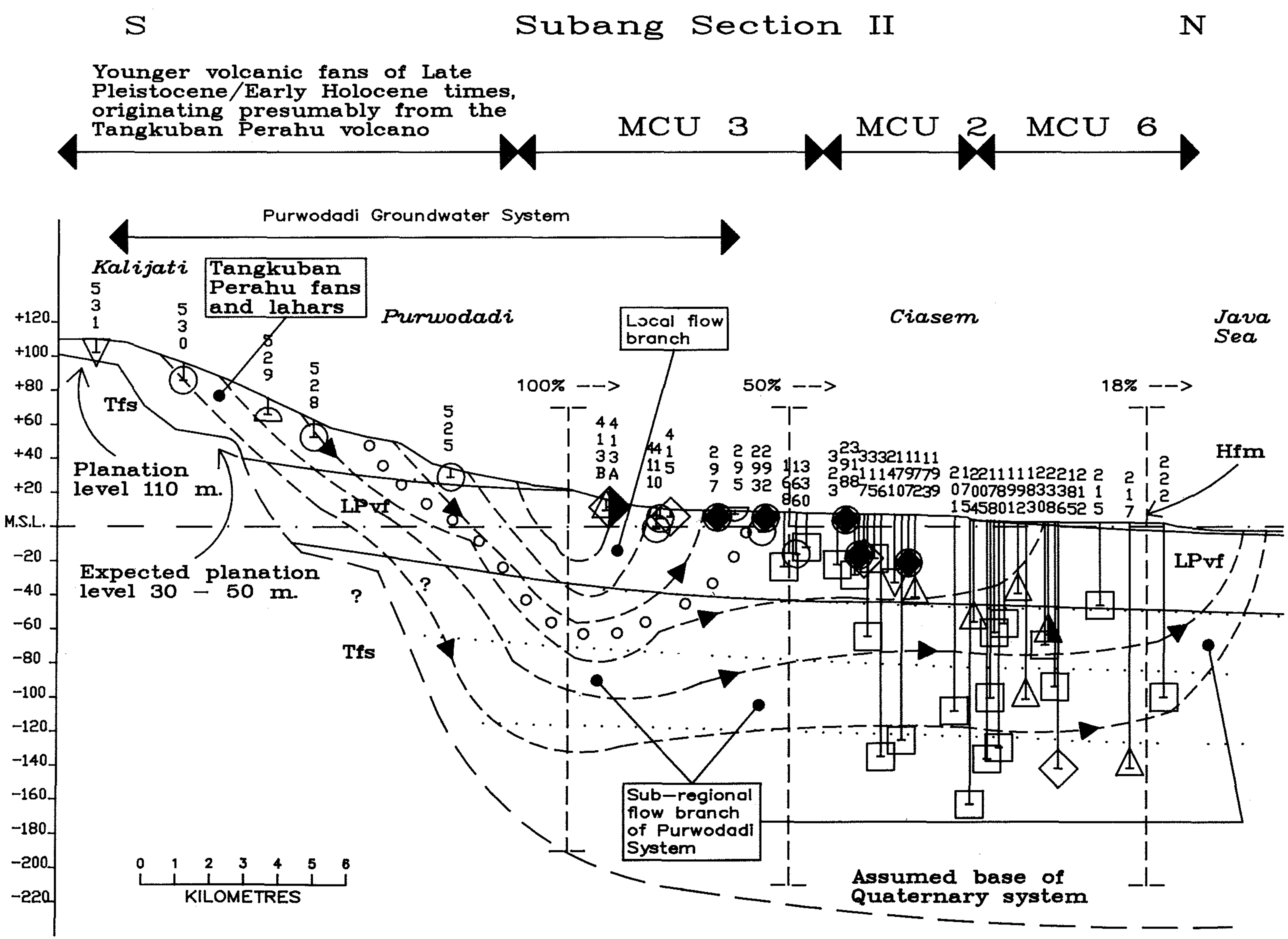


Fig. 7.14 Hydrochemical cross section Subang II (see Fig. 7.5 for general legend).

Wells located in areas where short streamlines emerge at the surface such as wells 410, 411, 413A, 413B and 415 (see Appendix II and Table 7.8), are characterized by low pH values which indicate leaching due to rapid groundwater circulation. Those parts of the Volcanic Fan Formation covered by flood plain clays deposited by the river Ciasem again exhibit mineralized shallow groundwaters of the brackish CaCl type, such as the wells 297, 292 and 298. However, at depths of 24 to 28 metres in the Volcanic Fan Formation similar brackish CaCl types are found, which may point to the presence of buried flood plain deposits as also interpreted from the lithological descriptions of the deep wells Pamanukan 1 and 2 (see Fig. 7.12). The majority of chemical types in the Volcanic Fan Formation are of the $CaHCO_3$ and $NaHCO_3$ type.

Extremely poorly mineralized groundwaters, probably due to unsaturated zone drainage of local precipitation water from previous rainy seasons, have been sampled in the middle of the dry season (August, 1983) from dug- and tube wells in the younger Late Pleistocene-Holocene volcanic materials between Kalijati and Purwodadi (electrical conductivity values less than 100 μmhos/cm).

To the south of the village Kalijati the planation level at about 110 m is undisputably present (mentioned also by Pannekoek, 1949) and covered by only a thin layer of young volcanic Tangkuban Perahu material. The second planation level at 30 to 50 m may be present beneath the volcanic cover as a buried landscape. A change in slope can be observed just south of the village Purwodadi which may reflect a continuation of the underlying planation level. In the mean time the 30 to 50 m level has not been positively identified as far as Purwodadi due to a lack of further evidence.

Table 7.9 Characteristic chemical types of groundwater in the young volcanic materials from section Subang II.

Id. Nr.	Depth (m)	EC μmhos/cm	pH	Chemical type
525	5.0	230	6.1	FO-CaHCO3+
528	10.0	90	5.3	F*-CaHCO30
529	10.0	28	5.6	F*-MgMix 0
530	10.0	45	5.7	F*-CaHCO30
531	8.0	27	5.3	F*-MgHCO30

The streamline pattern of groundwater schematically drawn in Fig. 7.14 supports the occurrence of fresh $NaHCO_3$ type groundwaters in the deeper layers. The steep topography on the young Late Pleistocene-Early Holocene volcanic fans and lahars from the Tangkuban Perahu generates a relatively strong groundwater flow with a flux of 0.98 m^2/d measured at the inflexion point of the streamlines. Due to continuation of an appreciable topographic slope in units 3 and 2, the major groundwater system stretches to the north to produce a flow which is sufficient for a remaining flux of about 50%. This flux is responsible for the flushing of the deeper layers. Near the coast the flux is further reduced to about

18%. In section Subang II two points at the surface can be identified with a concentration of ascending streamlines; the topographical inflexion points between units 3 and 2 and the boundary between units 2 and 6. This cross section resembles Karawang II, in which the coastal lowland morphology is dominated by the Late Pleistocene Volcanic Fan Formation represented by morphological units 2 and 3. A major groundwater system is present underneath the volcanic fan unit with apparently sufficient circulation to flush the deeper layers. This is almost absent in section Karawang I.

The section Subang III shows that the delta of the Cipunegara river has already built up a Holocene coastal plain 9 km wide, implying that here the coastal lowlands are not entirely dominated by the Late Pleistocene Volcanic Fan Formation as in the previous sections. Fresh $NaHCO_3$ groundwater types are found in the deeper aquifer horizons under exposures of the Volcanic Fan Formation. Varying groundwater qualities, mainly of brackish NaCl and NaMix types, occur beneath the Holocene coastal and deltaic plain north of the town of Pamanukan. However, the salinities of the deeper groundwaters, although generally unfit for human consumption, are far less than for sea water (see Table 7.10). Even tube well 17 near the coast still produced a fresh NaMix type of water in 1983.

The stratigraphy for this cross section is adopted from the two deep wells Pamanukan 1 and 2 (see Fig. 7.12). Again conspicuous is the good agreement between the tube well end depths and the statistically derived depth clusters.

Table 7.10 Characteristic chemical types of deeper groundwater under the Holocene coastal plain in section Subang III.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
1	120.0	750	7.5	F*-NaMix +
2	108.0	1,200	7.7	f*-NaMix +
4	72.0	6,500	7.4	B5-NaCl
6	108.0	1,100	6.9	f*-NaCl +
7	57.0	1,200	7.7	f0-$NaHCO_3$+
8	72.0	950	7.9	F*-NaMix +
9	72.0	1,050	7.5	F*-$NaHCO_3$+
13	54.0	1,250	7.5	f*-NaCl +
14	96.0	5,000	7.3	B2-NaCl 0
16	96.0	1,800	7.5	b1-NaCl +
17	96.0	1,050	8.0	F*-NaMix +

The main boundary between fresh and brackish deep groundwaters is fairly sharp and coincides with the boundary between morphological units 2 and 6.

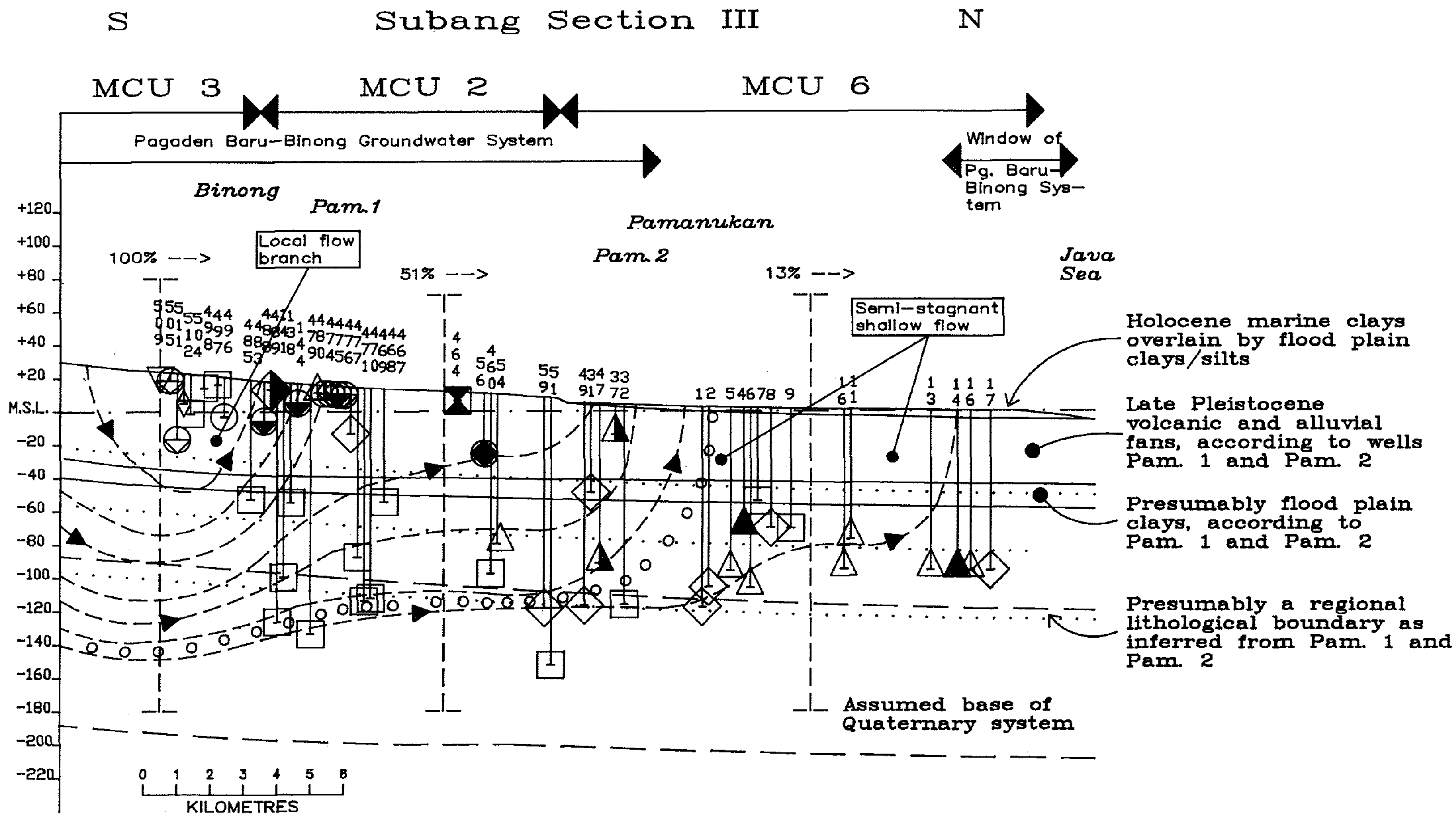


Fig. 7.15 Hydrochemical cross section Subang III (see Fig. 7.5 for general legend).

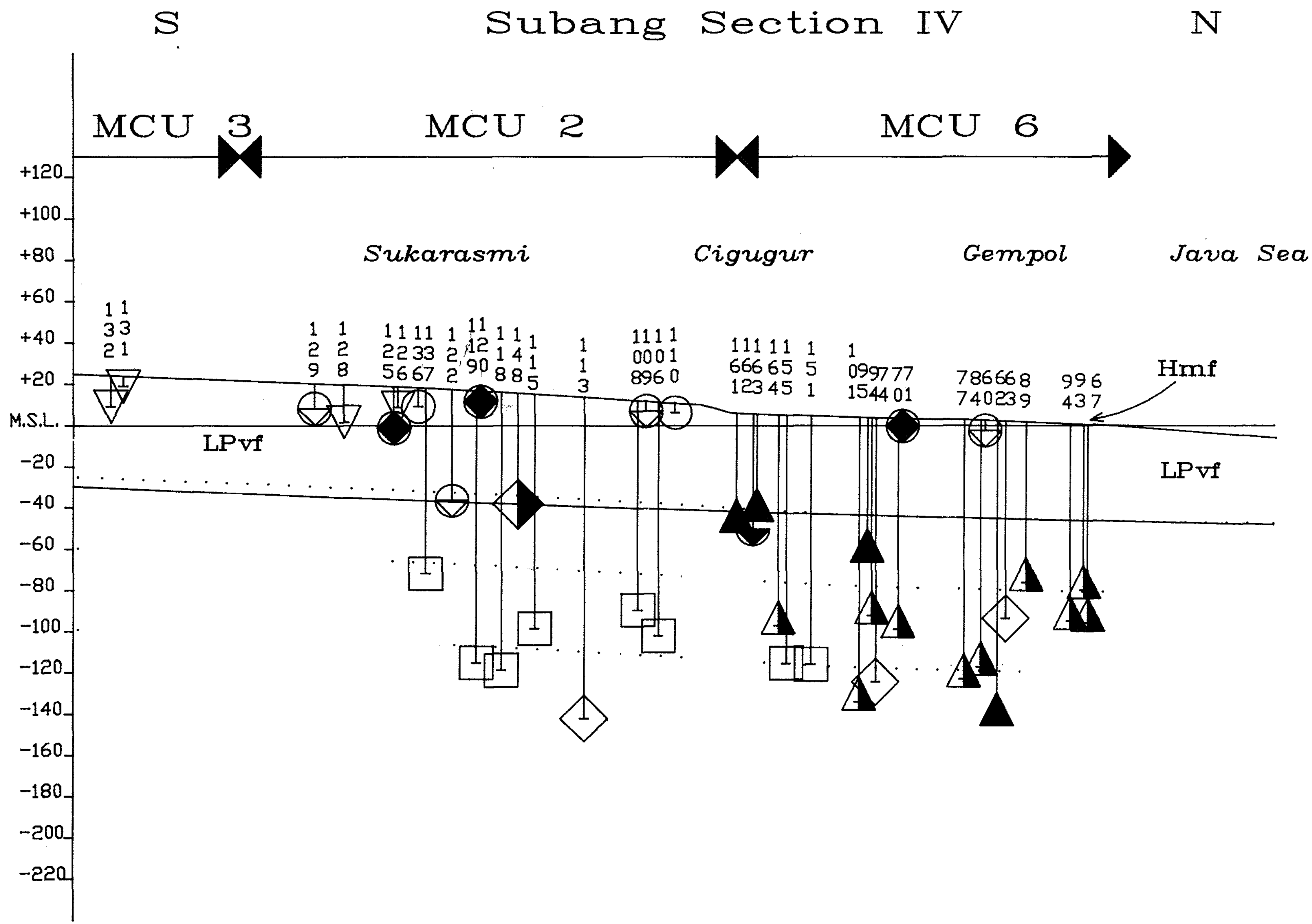


Fig. 7.16 Hydrochemical cross section Subang IV (see Fig. 7.5 for general legend).

In this cross section two locations with pronounced concentrations of ascending streamlines are evident; one at the boundary between units 3 and 2 and the other at the boundary between units 2 and 6. The topography on the exposed Late Pleistocene Volcanic Fan Formation, to be found as far as the town of Subang in the south, generates a groundwater flux of about 0.66 m^2/d as determined at the streamline inflexion points. Of this, 51% is still flowing beneath unit 2 in which most of the fresh $NaHCO_3$ types of deep groundwater are found. Finally, beyond unit 2 the flux is strongly reduced to only 13%. In this section it again appears that the major groundwater flow system induced by the topography of the Volcanic Fan Formation is responsible for flushing the originally saline pore waters in deeper layers.

Cross section Subang IV resembles the previous section with respect to water quality patterns in the deeper aquifer horizons. Beneath the Holocene coastal and deltaic plain mainly brackish NaCl types are found. Fresh and low hardness $NaHCO_3$ groundwater types are confined to areas where the Volcanic Fan Formation is exposed. Some of the chemical types of deeper groundwaters under the newly accreted coastal and deltaic plain are listed in Table 7.11.

Table 7.11 Characteristic chemical types of deeper groundwater under the Holocene coastal plain in section Subang IV.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
63	96.0	1,100	8.0	F*-NaMix +
67	96.0	2,100	7.6	b0-NaCl
70	108.0	3,600	7.2	b3-NaCl
77	126.0	2,900	7.5	b0-NaCl 0
93	80.0	3,900	7.6	b1-NaCl 0
94	96.0	1,300	7.9	b0-NaCl 0

7.5.5 *Conclusions on the groundwater hydrochemistry in kabupaten Subang*

The conclusions drawn for kabupaten Karawang also hold for Subang. Additional conclusions to kabupaten Subang are:

1) the groundwater qualities in the deeper permeable horizons are related to the major gravity-driven groundwater flow system in the coastal lowlands of Subang, which is generated by the topography of the Late Pleistocene Volcanic Fan Formation (morphological unit 3);
2) transitions in chemical types in the deeper permeable horizons coincide with concentrations of ascending streamlines;

3) brackish to salt NaCl and NaMix chemical types in the deeper layers are generally found in the proportionally poorly flushed zones beneath unit 6.

7.6 *Kabupaten Indramayu*

7.6.1 *General physical setting*

The kabupaten of Indramayu, similar to kabupaten Karawang, is characterized by an impressive delta of the Cimanuk river, which drains an extensive catchment of 3,375 km^2 in the volcanic arc of West Java. The Cimanuk has built up a high-constructive-elongate type of delta in the microtidal Java Sea in the northeastern part of the kabupaten. High rates of coastal accretion and destruction take place but the net effect is a strongly prograding and protruding coastline. Other important rivers draining areas outside the administrative boundaries of Indramayu are the Cipanas and Cipunegara. However, the latter diverts its discharge to the neighbouring kabupaten Subang. The remaining drainage pattern has a local nature only and originates on the Late Pleistocene Volcanic Fan Formation with its characteristic reddish coloured soil. The Cimanuk delta is drained by a secondary drainage pattern which is easily recognizable in the eastern part of the delta. Conspicuous is the absence of important rivers along the eastern coast of kabupatens Indramayu and Cirebon, resulting in low sediment loads and hence erosional type of coastline.

Kabupaten Indramayu can be divided into two parts; a slightly elevated western part with the Late Pleistocene Volcanic Fan Formation (morphological unit 3) exposed over vast areas, and a low eastern part built up by the Holocene flood plain and deltaic deposits of the Cimanuk river. As the shape of the Cimanuk delta may alter almost every year, the coastline shown in Fig. 7.17 (taken from map series 'Peta Ikhtisar Jawa/Madura, helai 8', 1951 at scale 1:250,000) does not fully reflect the present-day situation.

Folded Tertiary strata within the kabupaten administrative boundaries are found only as a narrow strip in the southwestern part along the border with kabupaten Sumedang. The giant lahar flow, identified by statistical slope vector analysis in Chapter VI as morphological unit 4, has also been drawn in Fig 7.17 despite the fact that the larger part is situated in the neighbouring kabupaten Cirebon. It is interesting to note that the administrative boundary between kabupatens Indramayu and Cirebon coincides with the northwestern edge of the lahar flow. Related to the giant lahar flow is the obscure eastern boundary of the Late Pleistocene Volcanic Fan Formation, which is exposed from Karawang to this end of kabupaten Indramayu. On the geological map (sheet Arjawinangun quadrangle, scale 1:100,000 by Djuri, 1973) the giant lahar flow is considered to be different from the Late Pleistocene Volcanic Fan Formation. The flow is attributed to 'young volcanic products', whereas the Late Pleistocene Fan Formation is described as a tuffaceous formation of early Quaternary age. The latter age assignment is considered by the present author to be erroneous, as shown by the lithological logs of wells Pamanukan 1 and 2 described earlier. Nevertheless, the problem of the eastern boundary of the abruptly ending Late Pleistocene Volcanic Fan Formation remains unsolved. A plausible solution is to assume that the Fan Formation continues under the present Cimanuk channel deposits as far as the anticlinal structure in the Tertiary Kaliwangu clays to the north of the Kromong complex in kabupaten Cirebon.

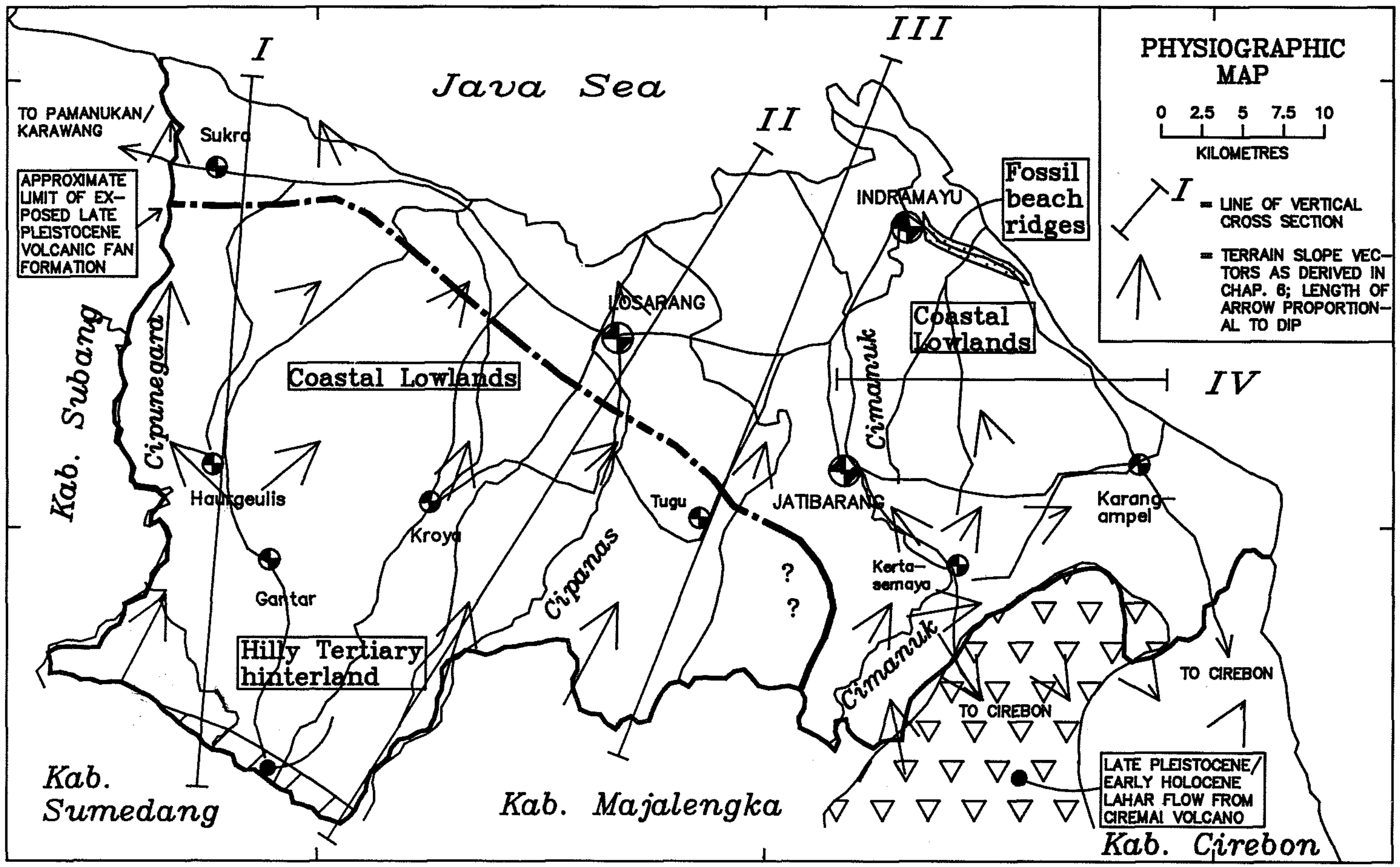


Fig. 7.17 General physical setting in kabupaten Indramayu.

This anticlinal structure must have acted as a barrier for the outward spreading of the fan material. The straight map boundary of the Late Pleistocene Volcanic Fan Formation is thus the result of incision by the Cimanuk river. The fact that the Fan Formation does not appear in kabupatens Cirebon, Brebes and Tegal, proves that the materials originated largely from volcanic eruption centres around Tangkuban Perahu volcano, north of Bandung. The abrupt disappearance in an eastward direction is then related to the peculiar anticlinal structure near the Kromong complex; it can be safely assumed that the wedge-shaped lithological unit terminates here.

Viewed on a regional scale the Late Pleistocene Volcanic Fan Formation has its maximum development in kabupaten Subang and lower fan segments in kabupatens Karawang and Indramayu. This may point to volcanoes in the vicinity of the Tangkuban Perahu complex as constituting the source of the volcanic fan. The approximate exposure limit of the Fan Formation in Indramayu curves from the boundary with kabupaten Subang rapidly towards SE and S directions. The position of the approximate limit of exposure, as drawn in Fig. 7.17, is mainly based on the change in terrain slope and corresponds roughly with the height contour of 6 to 10 m. Conspicuous is the straight valley of the river Cimanuk, trending SW to NE between the Late Pleistocene Fan Formation to the west and the giant lahar flow on the east. The direction of the Cimanuk valley accords with the mode in the histogram of slope vector trends in West- and Central Java (Fig. 6.2), thought to represent the original terrain slope of the Pleistocene land surface during the last glacial. The straight valley is maintained to the small town of Kertasemaya (see Fig. 7.17), beyond which the river curves sharply towards the town of Jatibarang and thereafter more or less follows the approximate limit of volcanic fan exposure. Tjia (1965) proposed that the sharp bend in the Cimanuk river at Kertasemaya is caused by a lahar flow from Ciremai volcano. However, it is difficult to imagine a lahar flow from Ciremai, east of the Cimanuk, pushing the river course at the west bank in a NE direction. It is more plausible to assume that the periphery of the Late Pleistocene Volcanic Fan Formation controls the Cimanuk river course.

The geomorphological evolution of the Cimanuk delta during the last 6,500 years has been described by Janssen & Dam (1985). Three phases of delta building are distinguished by these authors. In a first phase a delta was developed in an ENE direction with the apex located somewhere around Kertasemaya. The shore line, west of the delta during this first phase, may have run roughly parallel to the present-day limit of exposure of the Late Pleistocene Volcanic Fan Formation. In a next phase the delta had prograded in a NE direction, showing a general anti-clockwise rotation to the west characteristic for larger deltas of the northern coastal lowlands controlled initially by the Pleistocene land surface. In the final recent phase the delta migrated further north, accompanied by an anti-clockwise rotation in which the apex shifted from Kertasemaya to Jatibarang and finally to Indramayu. The delta lobes of the older phases were abraded leading to the typical arc-shaped eastern coastlines of kabupaten Indramayu.

The geomorphological evolution of shorelines in the northern coastal lowlands shows a similar pattern of a rapidly rising Holocene sea level due to deglaciation, which was hardly counterbalanced by sedimentation. The sea may have reached the present-day approximate limits of the Late Pleistocene Volcanic Fan Formation exposure, giving rise to the small cliffs found in kabupatens Karawang and Subang. Once the sea level rise stabilized sedimentation was capable of pushing the shore line northwards, thereby building the present-day morphological unit 6. At points along the shoreline where large sediment loads entered the Java Sea, such as at the Citarum and Cimanuk river mouths, rapidly prograding deltas developed in NE directions initially but gradually rotated to the N and NW.

From the viewpoint of hydrogeology, this model of coastal morphological evolution implies vast areas once covered by a shallow sea which have been converted to coastal plains/deltaic plains within a time span of only about 6,000 years. One may expect that in such dynamic sedimentary environments groundwater dynamics and chemical processes may significantly lag behind. The window along the shore with ascending streamlines of deeper groundwater flow, as shown in the previous cross sections, keeps pace with the rapidly shifting coastline. Groundwater particles situated in the bundle of streamlines will be subjected to movement. But as the window with the bundle of streamlines shifts, so do the flow system boundaries. Moving particles thus become trapped in the system of semi-stagnant very shallow groundwater flow which develops on the landward side of the window under the newly accreted coastal plain/deltaic plain. The end result will be groundwater bodies, once moved by the ascending streamlines, which have become trapped in semi-stagnant flow systems in which chemical equilibrium between aquifer materials and pore water has not yet been achieved. The continuously migrating delta lobes, characteristic for the Cimanuk delta, ensure constantly shifting flow system boundaries and thus preventing the establishment of boundary equilibria due to time lag effects.

7.6.2 General groundwater setting

The general groundwater setting in kabupaten Indramayu reflects the division into western and eastern parts. Fresh groundwaters, both at shallow and deep levels, are practically absent in the eastern section which was formed by the Holocene deltaic deposits of the river Cimanuk. Deep tube wells in the area around Indramayu and Lohbener often discharge methane-containing saline groundwaters under artesian pressures, with typical electrical conductivities of about 10,000 μmhos/cm.

The methane is derived from microbial decomposition of organic substances in fossil coastal swamp/mangrove swamp deposits. Many gas producing deep water wells are found, particularly west of the village Lohbener along the main road Jatibarang to Losarang.

Attempts at the beginning of this century to drill deep water wells in the towns of Indramayu and Jatibarang turned out to be failures, tapping only highly saline groundwaters[4]. On the other hand, sea water salinities have never been encountered so far. Shallow groundwaters for domestic water supply are also a problem. The flood plain clays of the Cimanuk river are characterized by saline groundwaters which are generally unfit for human consumption. Typical EC values of shallow groundwaters in the flood plain belt range from 2,000 to almost 10,000 μmhos/cm. Occasionally some local fresh groundwater bodies can be found in buried former channel- and beach sands of the older delta phases of the Cimanuk. As touched upon later, most of these buried shoestring sand bodies receive their fresh water recharge from irrigation channels which have been dug through the overlying flood plain clays down to the sand.

4 According to the water well archives at the Indonesian Geological Survey in Bandung a well drilled in Indramayu in 1909 (Archive no. 404) reached a final depth of 170 m with groundwater containing 5,000 mg/l Cl. Another attempt at Jatibarang in 1910 reached a depth of 187 m, yielding only salt water; the 'Jaarboek van het Mijnwezen', 1910, p:36, mentions gaseous brackish water only.

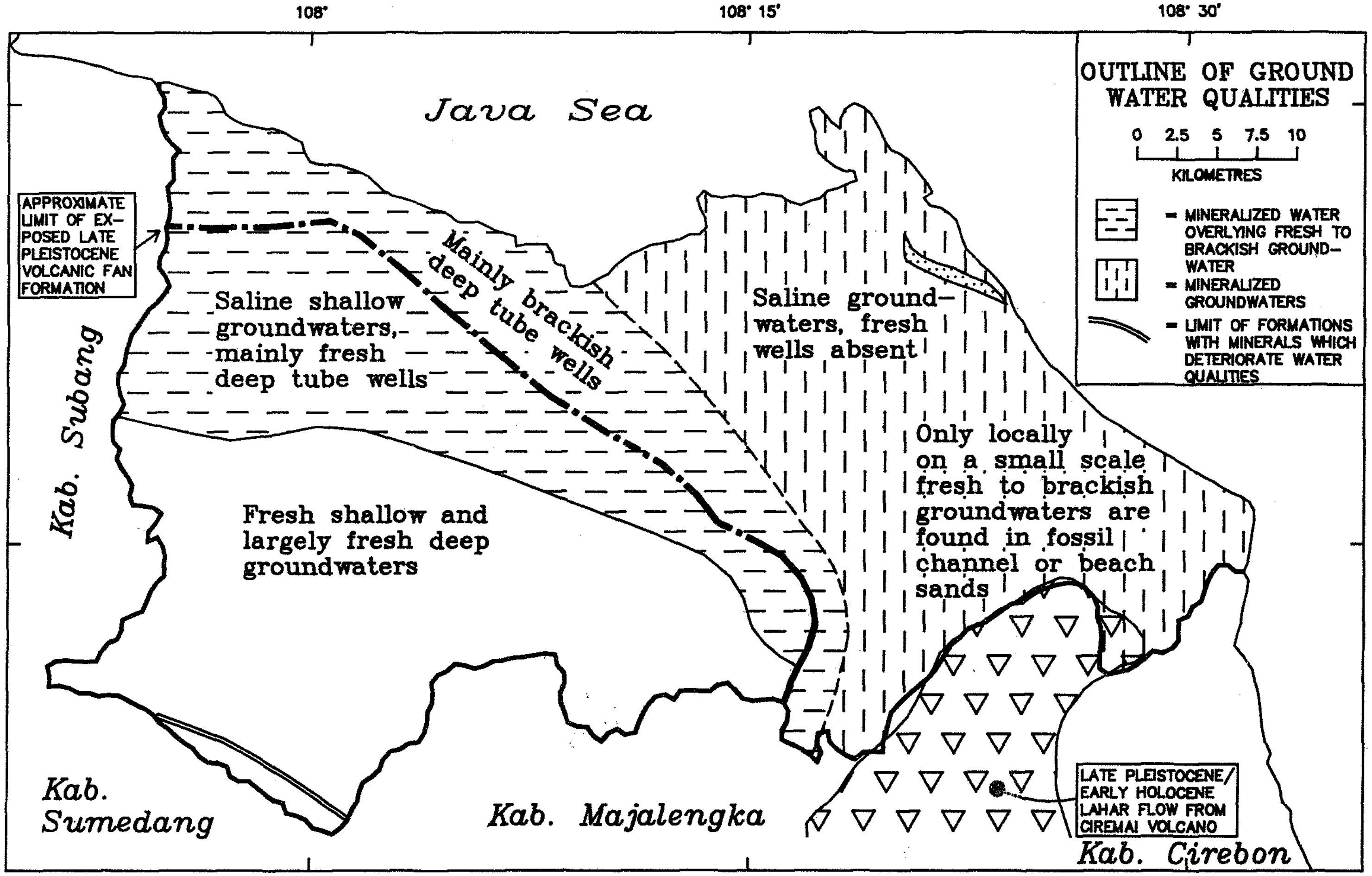


Fig. 7.18 Division of kabupaten Indramayu into major groundwater provinces.

Fresh shallow- and deep groundwaters are invariably available in areas with the exposed Late Pleistocene Volcanic Fan Formation. Deep tube wells in this area yield groundwaters with typical EC values of 500 to 700 µmhos/cm. Approaching the belt covered by flood plain deposits produces abrupt changes in shallow groundwater qualities. Mainly fresh deep tube wells are found to the approximate limit of volcanic fan exposure. Beyond this limit brackish deep groundwaters appear to prevail.

7.6.3 Hydrochemical cross sections through kabupaten Indramayu

Three cross sections have been constructed through kabupaten Indramayu. Contrary to the previously described kabupatens, the number of water samples collected during the 1980 to 1981 field campaigns is very limited due to the lack of adequate chemical laboratory facilities in the beginning of the OTA-33 project.

Cross section I through the western part of the kabupaten shows a topography dominated by the exposed Late Pleistocene Volcanic Fan Formation. At the boundary with the Tertiary hinterland a belt of coalescing Holocene alluvial fans is found, consisting of volcanic material derived from the extensive pyroclastic blankets on the higher planation levels which have now been dissected or largely removed by erosion. The influence of this alluvial belt at the break in slope on groundwater flow is limited.

Most of the deep tube wells beneath morphological zones 3 and 2, to the village Anjatan, yield groundwaters with EC values of about 700 µmhos/cm. Nevertheless, exceptions may occur such as tube well nr. 24 with a relatively high EC value of 2,300 µmhos/cm. The end depths of the wells in this section appear to fit into the third permeable horizon at about 120 m depth. Beyond Anjatan the electrical conductivities increase gradually to about 1,500 µmhos/cm. An interesting pre-war large diameter well is nr. 36 in the village Patrol. According to annals of the mining department of the Directorate of Geology in Bandung such as the 'Jaarboek van het Mijnwezen' this deep well was drilled in 1938 and chemical analyses were made of the well water immediately after implementation.

Table 7.12 Characteristic chemical types of deeper groundwater near the village Anjatan in cross section Indramayu I.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type		
34	0.0	1,350	8.4	f1-NaCl	0	
35	180.0	1,550	8.5	f*-NaCl	·	
36	146.0	1,800	?	b0-NaCl	+	Patrol, Sep.'80
36	146.0	?	?	b*-NaCl	·	Patrol, 1938
	144.0	?	?	F*-NaMix	+	Anjatan, 1938

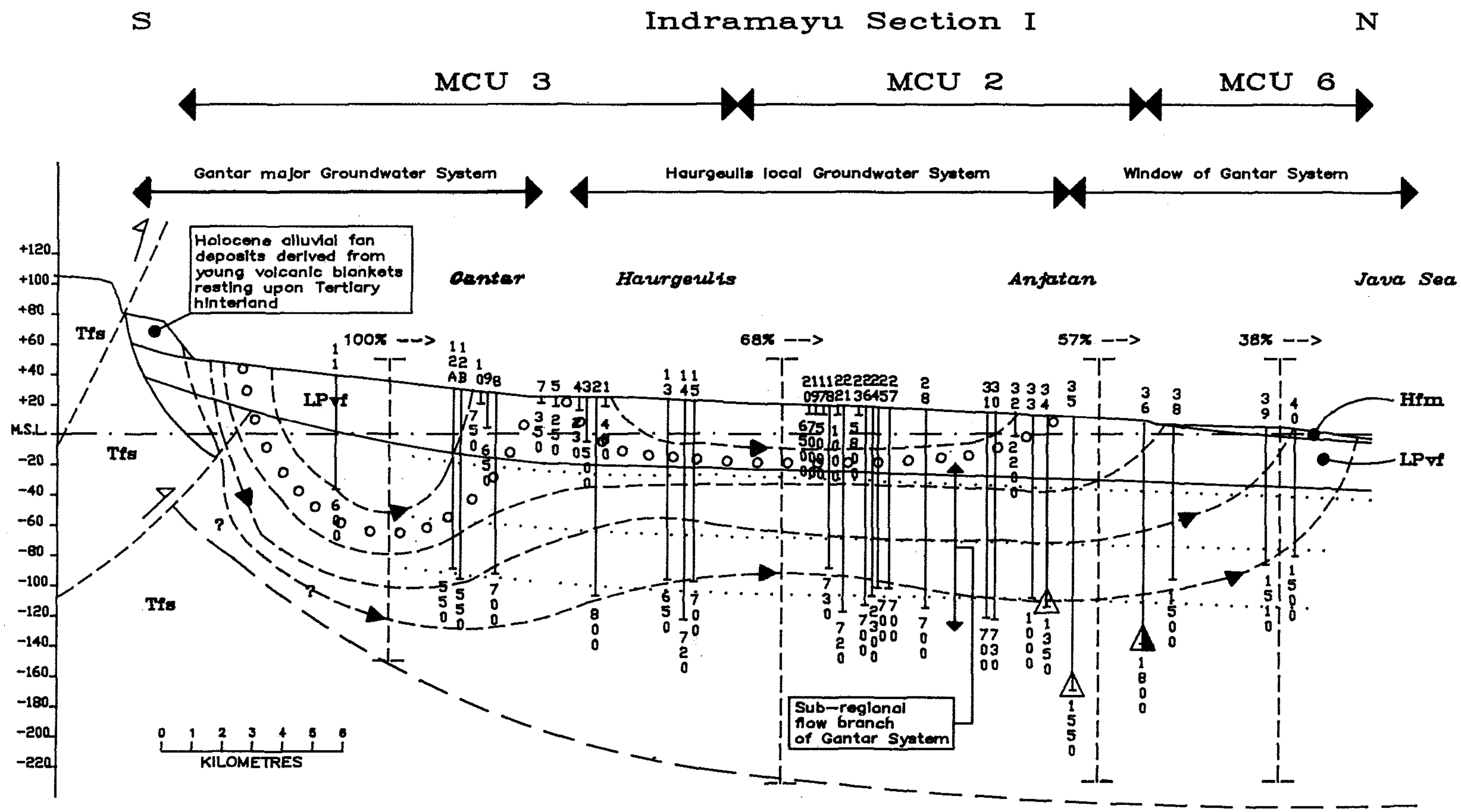


Fig. 7.19 Hydrochemical cross section Indramayu I (see Fig. 7.5 for general legend).

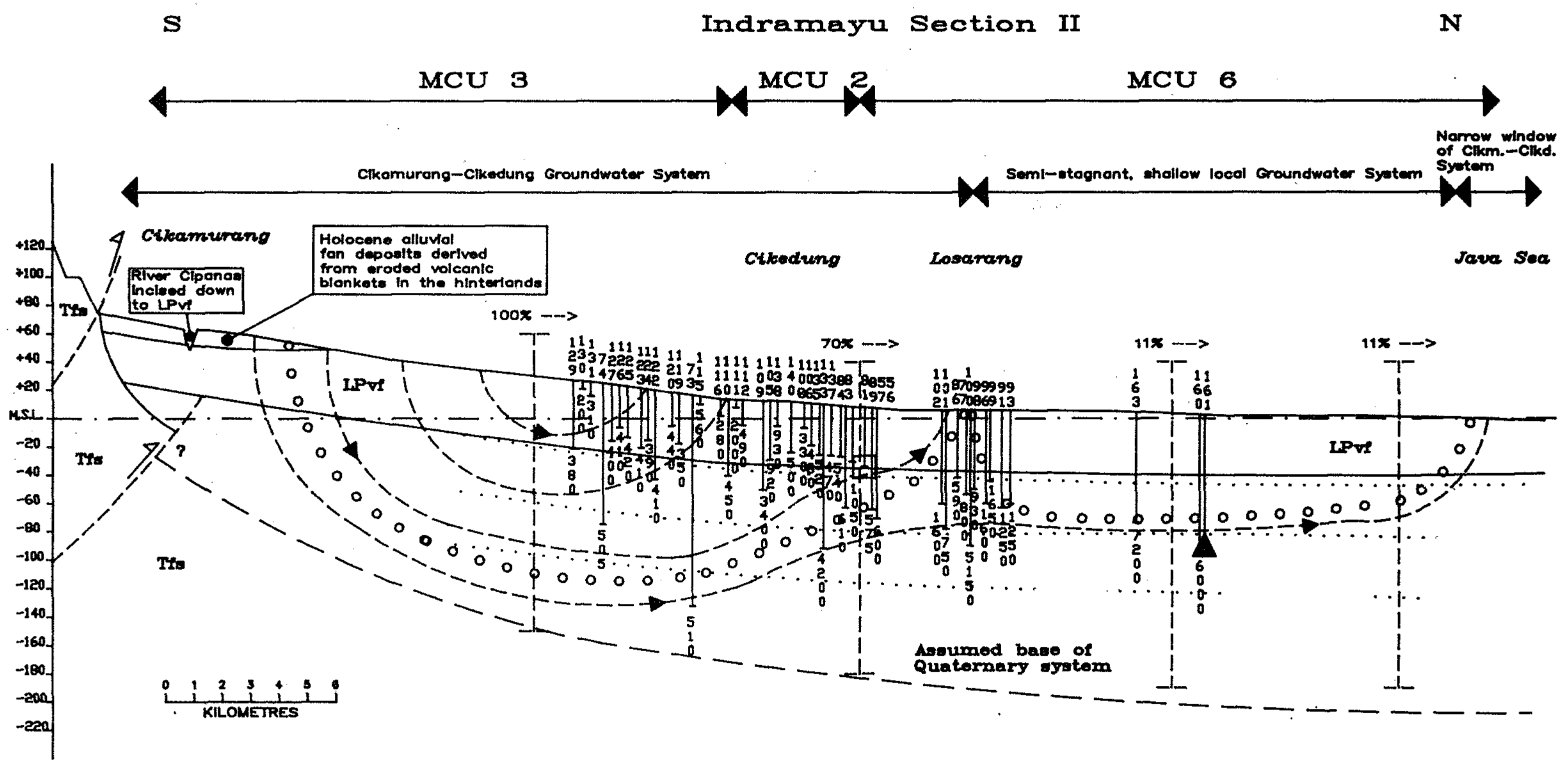


Fig. 7.20 Hydrochemical cross section Indramayu II (see Fig. 7.5 for general legend).

Chemical data are also available for a nearby deep well in the village of Anjatan which was drilled at the same time but already abandoned in 1980 (Jaarboek van het Mijnwezen, 1938, Bijlage II, p:62). These chemical data for the 1938 well waters have been classified according to the Stuyfzand procedure and are used for comparison with the water chemistry measured in September 1980 (see Table 7.12). It is remarkable to note both from this table and from the chemical analyses shown in Appendix II that the hydrochemistry of the Patrol deep well appears to be unchanged since 1938. Apart from some deep large diameter wells drilled under colonial rule, the significant number of tube wells found nowadays must have been entirely absent in 1938. The well water analyses of 1938 are thought to represent the original groundwater composition.

The percentages of groundwater fluxes calculated by FLOWNET to Anjatan are still high, which explains the well-flushed deeper permeable zones. Also according to FLOWNET, the amount of groundwater flow generated by this topography on the Late Pleistocene Volcanic Fan Formation is 0.32 m^2/day. This section resembles those in the vicinity of the boundary between kabupatens Karawang and Subang, the only difference being that in the latter two kabupatens higher fluxes are generated due to the steeper topography.

Towards the east the Holocene coastal- and deltaic plain association becomes gradually broader, as shown in cross section Indramayu II (Fig. 7.20). Electrical conductivities of tube well waters under morphological units 3 and 2 of about 500 to 700 μmhos/cm are comparable to those in cross section I. The strong reduction in groundwater fluxes from 70 to 11% beneath the Holocene coastal plain belt of unit 6 is reflected in the corresponding high EC values, which exceed 5,000 μmhos/cm. Widely varying groundwater qualities are found in the vicinity of Losarang where most of the streamlines ascend to the surface. This phenomenon, characteristic for groundwater flow windows, was also found in Karawang and Subang. The deep tube wells under morphological unit 6 invariably yield saline groundwaters with fairly constant EC values of about 7,000 μmhos/cm. Anomalously high EC values for deeper tube well waters are found at wells 109 and 133 with 3,400 and 4,200 μmhos/cm respectively. End depths of these two wells, do not fit any of the depth clusters and may therefore tap less permeable strata with connate saline pore waters.

Dug wells constructed in the Fan Formation without a flood plain clay cover as found in morphological unit 3 yield poorly mineralized groundwaters.

Indramayu section III covers the greater part of the Holocene deltaic plain of the Cimanuk river. The topography reveals an abrupt change in slope near the village Tugu (see Fig. 7.17) between the Late Pleistocene Volcanic Fan Formation and the young deltaic plain. The nature of this break in slope remains obscure. Its elevation at about +40 m excludes Holocene marine abrasion.

A plausible explanation, however, might be the effect of tectonic movements in this part of kabupaten Indramayu at the chronological boundary Late Pleistocene-Early Holocene and presumably also into the Holocene. The following arguments can be advanced which are thought to support this hypothesis of tectonic movements:

1) in Fig. 4.3 which depicts the major structural elements on Java and the surmised structural zoning, a concave lineament is shown which runs from the east coast of kabupaten Indramayu far into the kabupatens Cirebon and Brebes. This lineament can be recognized easily on LANDSAT images taken in 1972;

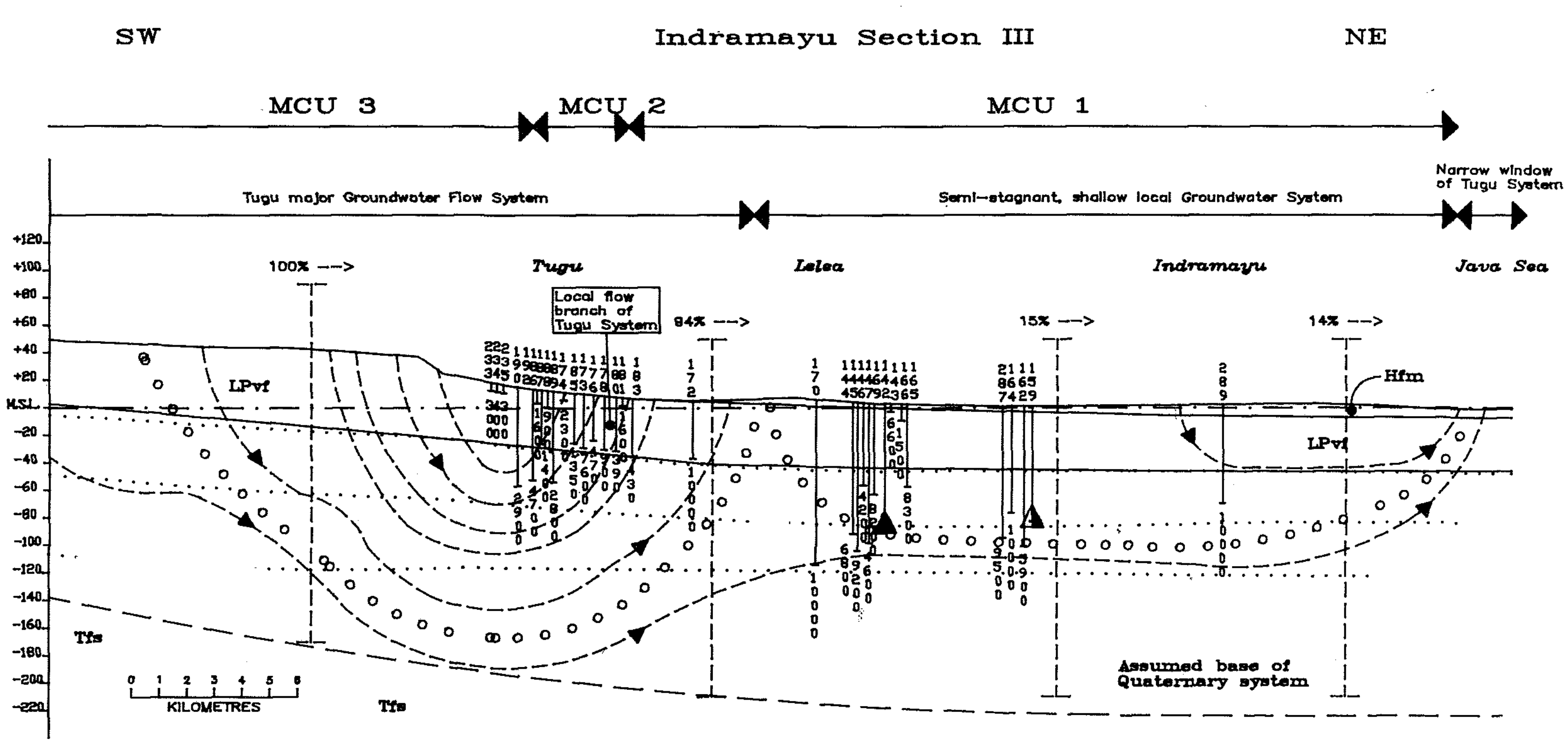


Fig. 7.21 Hydrochemical cross section Indramayu III (see Fig. 7.5 for general legend).

2) the E-W cross sections by Janssen & Dam (1985) through the Cimanuk delta reveal a normal fault-like structure at about 7.5 km east of Jatibarang in the underlying Late Pleistocene Volcanic Fan Formation;
3) the straight course of the Cimanuk river from Kertasemaya to Jatibarang is eye-catching and may indicate a structural control.

The step-like topography near the village Tugu might be well explained by tectonic movements along similar NW-SE concave normal faults forming part of a set of such faults up to the east coast of Indramayu. Even the shape of the eastern shore line is remarkable and unique for the northern coastal lowlands. The lineament recognized on the 1972 LANDSAT images coincides with the shoreline between Indramayu and Cirebon and may well bound the eastern side of an isolated hill, north of the town of Cirebon, which consists of Pleistocene Gintung volcanics.

The sudden break of slope has a considerable impact on the pattern of groundwater flow, as can be seen from the cross section in Fig. 7.21. A local flow branch of the groundwater system is generated by the topography around Tugu with a dense pattern of streamlines. A group of tube wells in the village of Tugu is situated in the ascending streamlines, which is again reflected in widely varying groundwater qualities over short distances which is thought to indicate the presence of a groundwater flow window. EC values range from 430 to as high as 4,700 μmhos/cm for the sample of surveyed wells.

Only highly saline deeper groundwaters are found to the north of Tugu under the low-relief Holocene deltaic- and coastal plain of the Cimanuk river. This explains the totally unsuccessful drilling attempts at the beginning of this century. However, it again must be emphasized that none of the surveyed saline deep tube wells exhibited EC values in the order of pure sea water and ranged from 5,000 to 10,000 μmhos/cm. The groundwater flow pattern and the remaining small fluxes of around 15% found beneath morphological unit 6 supports this groundwater quality picture.

7.6.4 Shallow groundwaters in the upper deltaic plain of the Cimanuk river

As a follow up to the 1985 Quaternary geology investigations by the students Janssen & Dam in the eastern part of the Cimanuk delta (Sheet 4623 I, Jatibarang, T725 map series, scale 1:50,000), hydrology students of both the Gadjah Mada University, Yogyakarta and the Free University, Amsterdam, conducted surveys of shallow groundwater in the same area. The principal objectives were to supplement the Quaternary geology maps with hydrological data and to study the groundwaters in each of the lithological elements of the delta.

Shallow groundwaters in the flood plain deposits of the northern coastal lowlands of Java, as discussed in the previous sections on the cross sections through the various kabupatens, are generally highly mineralized. Even shallow wells dug entirely within these young, stiff, grey, mottled clays of the flood plain deposits and situated well above present-day sea level may yield groundwaters with EC values of thousands of μmhos/cm. Striking examples will be touched upon in later descriptions of the kabupatens Brebes and Tegal. Another aspect of the shallow flood plain groundwaters is the strongly varying salinity, apparently unrelated to the presence of a nearby sea coast, irrigation channels or rivers.

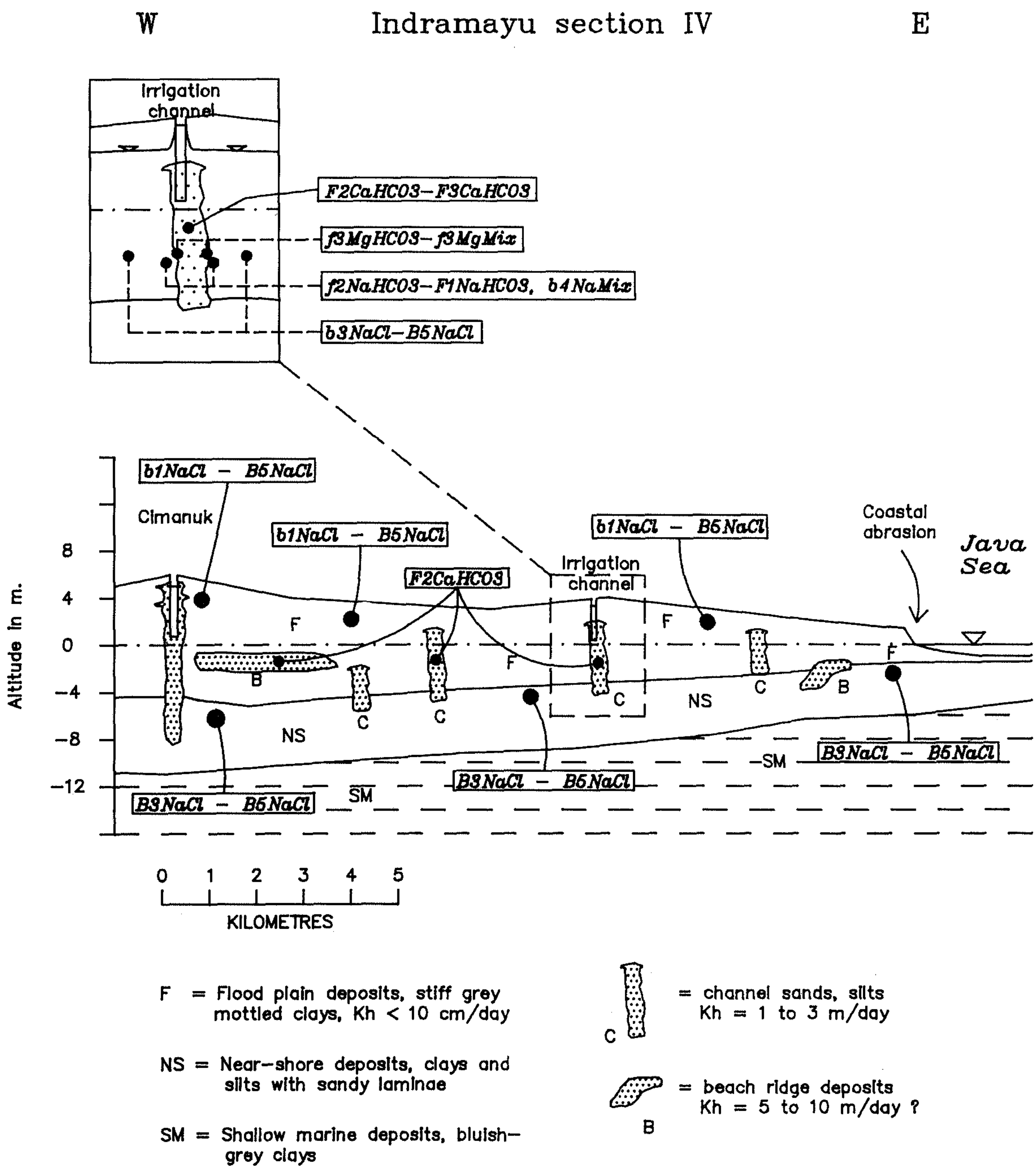


Fig. 7.22 Schematic E-W cross section from the Cimanuk river to the Java Sea, showing the characteristic chemical types of groundwater in the various lithological elements. Quaternary geological framework adapted from Janssen & Dam (1985).

A schematic cross section through the upper deltaic plain of Cimanuk delta in the Jatibarang sheet 4623 I is shown in Fig. 7.22. Most groundwaters in the flood plain clay deposits classify as b1-NaCl+ to B5-NaCl0 types, whereas wells penetrating the deeper nearshore deposits (NS) reveal mostly B3-NaCl0 to B5-NaCl0 types. During the survey at the end of 1986, groundwater levels in the flood plain clays were found at about 2 m below the surface in the middle of the section and at 4 m near the Cimanuk river. Interesting are the brackish groundwaters in the flood plain clays, even in the direct vicinity of the Cimanuk river, at locations which are out of reach of any salt water tongue which may penetrate the river during the dry season. Dug wells tapping groundwaters from sand horizons, hydraulically connected to the channel sands yielded fresh waters and the water level in these wells reacted clearly to Cimanuk discharge fluctuations. The saline dug wells in the flood plain clays reportedly lacked any reaction to the river. Table 7.13 lists a few water samples from dug wells on the eastern bank of the Cimanuk river south of the town of Indramayu near the village Lohbener. Wells 69, 70 and 71 reach sandy horizons and react to Cimanuk water level fluctuations; reflected in the chemical types which indicate the fresh water flushing of salt sediments. Well 76 reportedly penetrated sand and its groundwater chemical type suggests a nearly end stage of fresh water flushing. The saline B4-NaCl type wells appeared to be dug entirely in flood plain clays.

Table 7.13 Characteristic chemical types of shallow groundwater in the flood plain clays of Cimanuk delta.

Id. Nr.	Depth (m)	EC μmhos/cm	pH	Chemical type
69	3.1	1,300	7.9	F2-$NaHCO_3$+
70	3.6	1,300	8.0	F2-$NaHCO_3$+
71	3.0	2,220	7.9	b3-NaMix +
72	3.2	1,350	8.1	F2-$NaHCO_3$+
73	4.7	5,530	7.9	B4-NaCl
74	4.6	4,810	7.9	B4-NaCl
76	3.1	877	7.7	F2-$MgHCO_3$+
286	2.6	7,370	7.3	B5-NaCl

Comprehensive reactions of dug wells in pure flood plain clays are the nearly constant water levels during the dry season in combination with saline groundwaters, followed by fast rising watertables during the first showers of the wet period and substantially better groundwater qualities which again deteriorate gradually at the end of the wet season. This behaviour of clays subjected to desiccation has also been described at length by Terzaghi & Peck (1967, p:148). A similar situation was encountered near irrigation channels containing fresh water, with an apparent lack of any reaction or relation by the shallow groundwaters in pure flood plain clays to the nearby open channels.

Auger holes up to 4 m deep have been drilled along seven profiles over a total length of 400 m perpendicular to the coast at the beginning of December 1986. As shown in Fig. 7.22 active wave induced coastal erosion takes place constantly within the flood plain clays. The following results were obtained from the auger drillings:

1) strong contrasts between the EC values of the sea, at that time about 41,000 μmhos/cm, and those of groundwaters in the flood plain clays (averaging around 15,000 μmhos/cm) at only a few metres from the sea or even at the foot of the small cliff near the village Dadap;
2) the water table in the flood plain clays was elevated (less than 25 cm) slightly above estimated mean sea level in all profiles with the exception of those in the former beach ridges;
3) again the EC values varied strongly and the effects of former brackish shrimp breeding ponds and salt pans were reflected in high EC values exceeding 50,000 μmhos/cm.

Another striking aspect of the groundwater hydrology of Cimanuk delta is the presence of fresh confined water in most of the buried channel- and beach ridge sands. These shoestring sand bodies are the remnants of former Holocene development phases of the Cimanuk delta, at times when the delta prograded in a NE direction. The majority of built-up areas in the villages follow exactly these underlying shoestring sand bodies, even when completely buried by younger flood plain clays. The reason is evidently related to the strong shrinking and swelling capacities of the predominantly montmorillonitic clays, which affect building foundations. Auger hole drillings above a buried sand body reveal first the saline shallow groundwaters of the overlying flood plain clays, but further augering will reach the roof of the sand body and suddenly the water level in the drilling hole rises a few tens of centimetres or may even become artesian. The electrical conductivity of the water in the sand bodies is substantially lower and can be classified as fresh. The local villagers usually know where to dig wells to tap the fresh groundwater containing sand bodies. Since most of the sand bodies are under confined pressure a flow direction can be expected to exist towards the enveloping saline flood plain clays. This hypothesis is confirmed by the hydrochemistry of dug well water in the surroundings of buried sand bodies. Wells tapping the sand bodies generally yield F2-$CaHCO_3$+ type water, whereas at the periphery with the flood plain clays f3-$MgHCO_3$ types are found. Still further away f2-$NaHCO_3$ to b4-NaMix types occur and finally the common b3-NaCl to B5-NaCl types. This series clearly indicates flushing of the enclosing saline clays by the fresh groundwaters under confined pressure. Occasionally the reverse is found and saline groundwaters from the enveloping clays may intrude the sand bodies if the confined pressure is lowered by excessive withdrawals. This leads to b4-CaCl water types characteristic of salt water intrusion. The confined pressure conditions in the buried channel sand bodies and fossil beach ridges are generated by the major irrigation canals in the area which are dug sufficiently deep to penetrate the roof of the shoestring sand bodies; confirmed by field surveys after drilling into the canal floors. The depth of most of the major irrigation canals is about 4 m.

What could be the source of salts giving rise to these saline groundwaters in the flood plain clays? Highly saline groundwaters in the underlying near-shore deposits and marine clays, as penetrated by the deeper dug wells, is fully understandable and must be related to connate pore waters, which are not yet flushed. However, the young flood plain clays and silts have been deposited during floods under purely fresh water conditions far above the present sea level. The habitual mechanism of salt water intrusion can thus be completely excluded. The following main features of saline groundwaters in the flood plain clays and silts are thought to be in contradiction with a mechanism of salt water intrusion:

1) saline groundwaters are found in young flood plain clays deposited on, for example, the Late Pleistocene Volcanic Fan Formation far away (tens of kilometres) from the present coast and at altitudes far above maximum Holocene sea levels. Thus any relation between the strongly varying salinities and distance from the sea is totally lacking;
2) present-day fresh water intrusions into the flood plain deposits from the Cimanuk river and the irrigation canals are practically absent as shown in the discussions above; also absent is salt water intrusion along the present-day coast;
3) the horizontal groundwater flow in the clayey sediments under these very small hydraulic heads and poor horizontal conductivities can be disregarded.

There are two mechanisms which may be invoked to explain the relatively high salinities of groundwaters in the flood plain deposits as compared to the poorly mineralized irrigation- river- and rain waters. The first mechanism is mineralization by dissolution of soluble substances present in the predominantly montmorillonite clays in the flood plain deposits and as an alternative, salinization by evapotranspiration might be considered. It should be borne in mind that the provenance area of the flood plain clays or in general the suspended load in streams crossing the coastal lowlands, consists for the larger part of Tertiary mudstones, clays and shales, all deposited in marine environments. The mechanism of salinization of shallow groundwaters by evapotranspiration is based on the fact that horizontal groundwater flow is practically absent in the Cimanuk delta; in general very sluggish groundwater flow can expected in the morphological units 1 and 6. From this it follows that in the present-day situation the major outflow component must consist of capillary rise and subsequent evapotranspiration, eventually leading to slow accumulations of salts in the soils which return to the watertable by percolation of precipitation or irrigation waters. Originally, before clearing the native vegetation and reclamation these lower parts of the flood plains must have been waterlogged and covered with extensive fresh water swamps in the absence of proper discharge facilities for surface water. The groundwater table must have risen almost to the surface and vegetation water demand was probably largely met by stagnant surface waters after floods or rainstorms. Today with wet-rice cultivation it can be expected that the bulk of the water demand is supplied by irrigation. Only those areas of the flood plains not receiving irrigation water all the year round are prone to depletion of groundwater by evapotranspiration.

Interesting data concerning soil salinities have been kindly obtained from IWACO. Five auger holes were drilled in the area SE of Indramayu on September 24, 1987, for the purpose of soil sampling at 10 cm intervals. The research and development laboratory of the Indonesian Irrigation Department (Puslitbang Pengairan) at Bandung analysed the samples for moisture and chloride contents of the dry soil. Results of the soil chloride contents versus depth are shown in Fig. 7.23. These curves demonstrate that the chloride content is highly variable both as a function of depth and between bore holes. Another conclusion is that any equilibrium between groundwater salinity and the chloride content of the dry soil is apparently lacking.

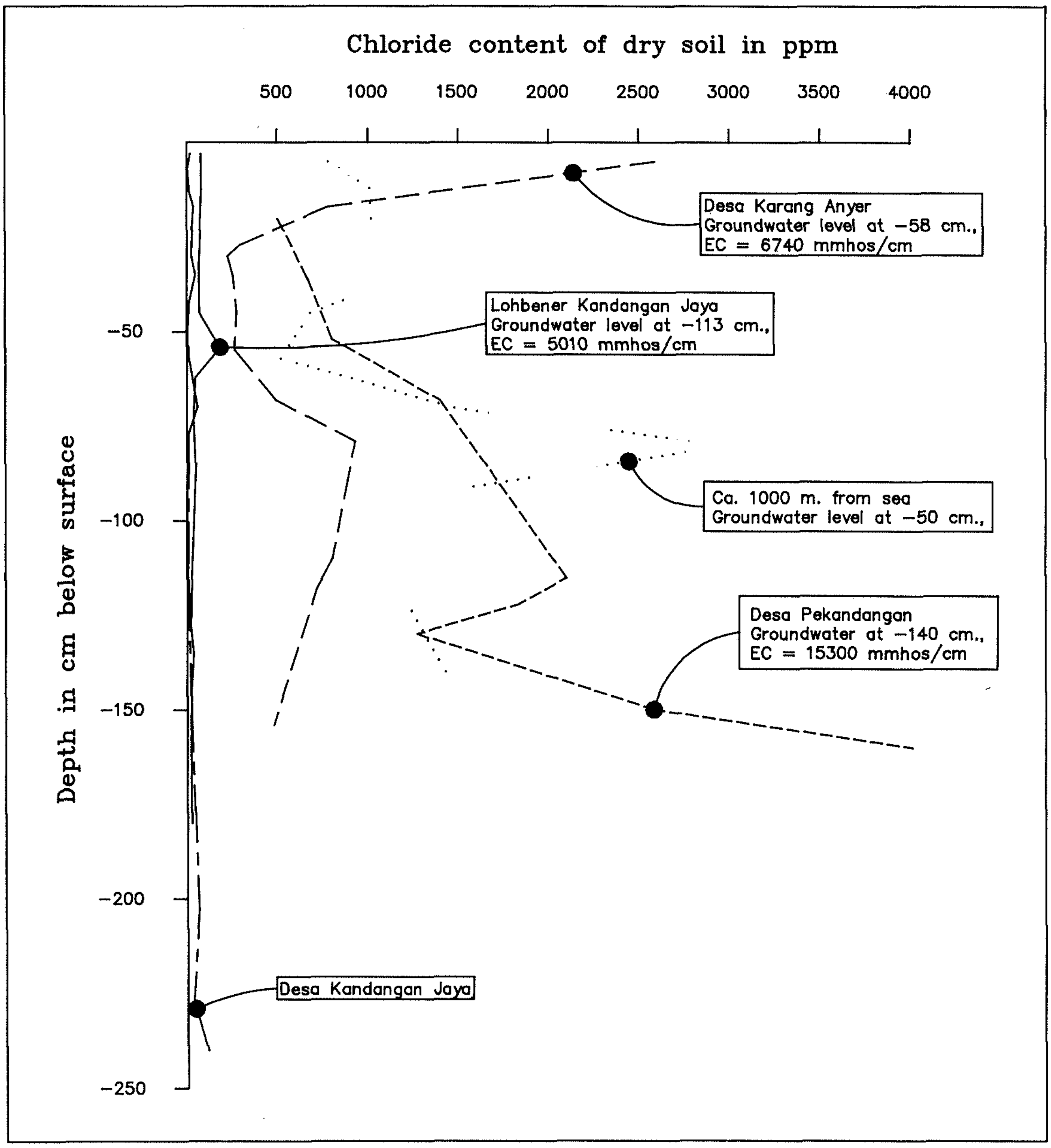


Fig. 7.23 Chloride profiles at the end of the dry period (September, 1987) in the flood plain area SE of the town Indramayu.

Returning to the two postulated salinization mechanisms, the following arguments can be advanced in favour of an evapotranspiration mechanism:

1) regional groundwater flow is practically lacking in the flood plain deposits, as shown by the hydrochemical cross section discussed so far. From cross section Indramayu IV it follows that available hydraulic gradients from river Cimanuk to the coast are in the order of 0.2 m/km;
2) deeper percolation can be ruled out in the flat parts of the flood plains and because of poor hydraulic conductivities in the underlaying near-shore- and marine clays. Only in the vicinity of river Cimanuk and major irrigation canals local groundwater flow systems are to be expected. This leaves for the larger parts of the flood plain only the outflow component of evaporated capillary risen groundwater and transpiration by plants;
3) this part of the Cimanuk delta is faced with annual shortages of irrigation water supply leading to fallow rice fields with desiccation cracks.

It follows that under these circumstances direct evaporation of soil can be expected on semi-technically irrigated rice fields. The hypothesis of direct evaporation of vadose water as a major salinization mechanism can be further tested by considering oxygen and deuterium isotope fractionations. ^{18}O and deuterium (D) δ-values of phreatic groundwater samples can be compared with known values for Jakarta precipitation (IAEA station).

Samples from four shallow wells in the Jatibarang sheet 4623 I have been isotopically analysed at the Isotope Physics laboratory of the University of Groningen, The Netherlands. The results are given in Fig. 7.24 and show the fractionations of deuterium versus ^{18}O in a standard diagram (Mook, 1984; Fontes in Fritz & Fontes, 1980). The sample plotting points suggest to be nicely arranged near the meteoric water line and seem to cluster around the weighted average values for Jakarta precipitation. None of the data points are located near the evaporation lines with slopes of the relationship between ^{18}O and D ranging from 4 to 6. However, if the data point in the lower left edge of the diagram is correct, the points lie on a line with a slope between 4 and 6. It should be emphasized that deuterium values for annual average Jakarta precipitation for the years 1962-64 and 1974-79) vary between -41 and -30 $^0/_{00}$. Nevertheless, no firm conclusions can yet be drawn. Even when the stable isotope analyses do not indicate direct evaporation of soil water, transpiration by vegetation may still be responsible for water loss from a soil and accumulations of salt in root zone which may percolate to the water table. Transpiration is generally assumed to be non-fractionating (Zimmerman et al., 1967; Barnes & Allison, 1983; Allison & Hughes, 1983).

Another technique is to compare the average ion ratios in flood plain groundwaters with those of the chemical endmembers, in this case pure seawater and average Cimanuk river water. Table 7.14 gives the ion ratios for 44 samples from shallow groundwaters in the flood plain clays of the Cimanuk delta, all belonging to chemical types NaCl and NaMix. The One-sample Z-test is applied to test for significant differences between the ion ratios in these NaCl/NaMix type groundwaters and those in standard sea water. In all cases the null hypothesis is rejected (at a two-tailed 5% level) from which it can be concluded that significant differences exist. However, the ion ratios of the NaCl/NaMix types much better resemble those in standard sea water than do the ratios for average Cimanuk river water.

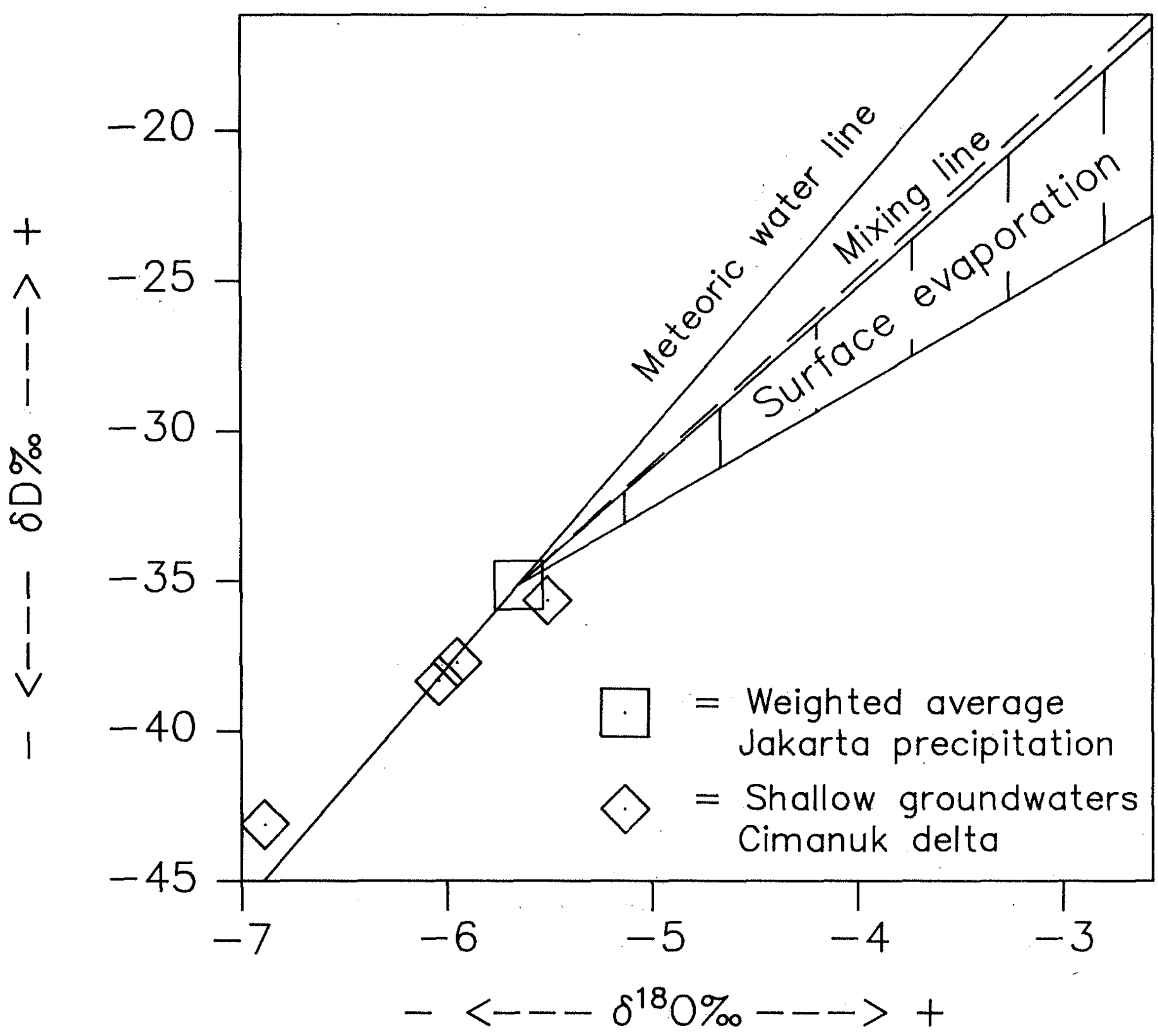


Fig. 7.24 Stable isotope composition of δ^2H and $\delta^{18}O$ in four samples of shallow groundwater in the flood plain deposits of Cimanuk delta.

Nevertheless, one is still faced with the problem of stagnant groundwater bodies in the lower parts of the flood plains. In the absence of groundwater flow one may expect that evaporation residues in clayey top soils with desiccation cracks, found along cross section Indramayu IV, will reach the watertable after the first showers at the beginning of the rainy season. On the other hand it should be realized that these waterlogged flood plains were inundated annually before erection of the major waterworks both by heavy storm or stream flooding. Strong swelling of the desiccated clays after the first downpours results in a rapidly rising watertable which may even reach the surface. Additional precipitation or flooding causes inundation.

Table 7.14 Averages of ion ratios for 44 samples of shallow groundwater in the flood plain clays of Cimanuk delta belonging to the NaCl and NaMix types. The One-sample Z-test (two-tailed) is used to test whether the average ion ratios of 44 water samples differ significantly from those of standard sea water. The null hypothesis, stating that the mean ion ratio = ion ration of sea water, is accepted if the calculated Z-test statistic falls in the range from -1.96 to +1.96 (5% two-tailed significance level).

	Na/Cl	Ca/Cl	K/Cl	Na+K/Cl	Mg/Cl	Cl/HCO_3	SO_4/Cl
NaCl/NaMix types							
Average ion ratios in 44 water samples	.76	.18	.05	.80	.10	2.65	.51
St. deviation	.30	.12	.07	.31	.07	2.57	.48
Ion ratios in standard sea water (Stumm & Morgan, 1981)	.56	.02	.02	.58	.07	136.30	.14
One sample Z-test statistic (*) (H_0 : Mean ratio= ratio sea water)	4.49	8.80	2.39	4.85	3.45	-341.54	5.05
Average ion ratios of Cimanuk river (IWACO/WASECO, 1987a)		2.04		1.14	1.04	.10	1.62

(*) listed in the table is the test statistic of the Z-test with standard Normal distribution N(0,1)

As the evaporation residues are concentrated in the root zones and top soil layers, it stands to reason to assume that these precipitates may be dissolved by rising water tables and subsequent inundations to be carried off as surface runoff to the secondary drainage systems. Only the semi-technically irrigated fields are sensitive to enrichments of evaporation residues in the top soil layers; the supply of water on permanently irrigated rice fields can be expected to meet the evapotranspiration demand. The purport of this discussion is that although soil evaporation can be expected to occur on these semi-technically irrigated fields lying idle for months with desiccation cracks, the evaporation residues will most likely not be transported downwards due to strong swelling of the clays and dissolution by inundating waters, leading to removal.

The following general arguments can be advanced which disagree with evaporation as the salinization mechanism:

1) the discrepancy between ion ratios in flood plain groundwaters and the ratios in average river Cimanuk water, acting a source for irrigation;
2) the chloride contents in the soil profiles, sampled at the end of the dry season, do not resemble the typical 'bulge-type' profiles (Allison in Simmers (ed.), 1988). At the end of the dry period in particular one may expect a maximum chloride concentration in the root zone, which is not apparent from the profiles;

3) at every location where flood plain clays are present saline shallow groundwaters can expected, even in well-drained areas where the Late Pleistocene Volcanic Fan Formation is covered by an incised veneer of flood plain clays;
4) the effect of salinization by evaporation should be noticeable in only the root zone or in the top layers of the clays with the desiccation cracks at the end of the dry season, whereas the saline groundwaters are omnipresent in the flood plain clays.

The alternative salinization mechanism caused by contamination with interstitial solutions in micro-pores and dissolution of solvable solids with ions adsorbed to the predominating montmorillonite clays of high exchange capacity thus accords much better with the field data. Billings & Williams (1967) report an average of 1,466 mg Cl^-/kg clay sediments. An interesting feature of the Tertiary hinterland with its unleached marine shales, marls and mudstones is the omnipresence of highly saline groundwater seeps and shallow local saline groundwater bodies. Groundwater runoff in the hinterland during the dry season reaches EC values of several thousands of μmhos/cm with values of 10,000 μmhos/cm frequently exceeded in small creeks and seepages. Even in the wet season EC values of many surface waters exceed 1,000 μmhos/cm. Seepages and small springs issuing from fault planes exhibit high salinities corresponding to those of sea water. Thus it can be concluded that the present pore waters of the Tertiary marine strata still resemble those entrapped during sedimentation, as can be expected in these monotonous series of mudstones, marls, clays and shales.

By studying the sedimentary process of flood plain clay deposition more insight may be gained into the nature and layering of these fine-grained deposits. Flood plain clays are deposits typically produced by large scale floods, during which the natural levees are overtopped and vast areas become inundated. The actual sedimentation process is very rapid from a geological point of view, producing a blanket of soft clay and mud several centimetres deep within a few days. Rapid sedimentation processes require on the other hand large loads of material which may be stored temporarily in the stream channels or released by active erosion. A typical scene during high discharges and excessive rainfall in the hinterlands shows numerous landslides, earth flows and other types of slips, and wide spread undercutting of river and stream banks, which releases huge amounts of fine-grained debris. Part of this debris is subsequently transported to the coastal lowlands where deposition and settling takes place in the vast inundated areas on the flood plains. These highly episodic and irregular processes of erosion, transport and deposition fall into the category of catastrophic sedimentary processes. Since energy levels are several magnitudes greater than during normal sedimentation, it stands to reason that fine-grained debris transported during these catastrophic processes consists of small lumps or flocs of marine fine-grained argillaceous rocks. These lumps may still contain the original saline connate pore waters, since the rapid stream transport prevents flushing. Van Genuchten & Cleary (in Bolt (ed.), 1981, p:379-382) after experiments with moving solutes in clay soils, stress the importance of mobile and in particular immobile concentration distributions in clay soils. Immobile regions of aggregates seem to exist which are difficult to leach by a bypassing wetting front. The existence of immobile liquid zones is also noticed by other workers and the amount of this 'dead water' may even exceed 50%. This effect might be expressed in the chloride profiles shown in Fig. 7.23, which display highly varying chloride contents versus depth. Each flood period may deposit a clay layer of a few centimetres with totally different chloride contents in the clays as result of different flood conditions, provenance areas etc.

7.7 *Kabupaten Cirebon*

7.7.1 *General physical setting*

The kabupaten of Cirebon with an area of 974 km^2 is situated at the transition between structural zones II and III as shown in Fig. 4.3. Unlike the kabupatens described so far with their broad coastal lowlands and structurally fairly monotonous hinterlands, kabupaten Cirebon has many geological and morphological contrasts. The conspicuous coastline curves sharply to the south which results in rapidly narrowing coastal lowlands down to a strip of only 3 km near the town of Cirebon. Towards the east the coastal lowlands broaden gradually, though not attaining the full 40 km width of structural zone II. Most of the morphology of the kabupaten is dominated by the huge and highly symmetrical cone of Ciremai volcano with its summit at an altitude of 3,078 m.

It follows that in a morphological setting with such a huge obstacle as the Ciremai cone, large rivers such as the Cimanuk and Citarum with catchments near the longitudinal axis of the island are absent. The largest river in this kabupaten, the Cisanggarung river with a watershed area of 925 km^2, is found at the eastern administrative boundary with kabupaten Brebes. The majority of surface water drainage systems originates on the northern and eastern slopes of Ciremai.

The giant lahar of Late Pleistocene and Early Holocene age, reflected in the slope vectors, descended from the northwestern slope of the volcano and flowed around the western side of the Kromong complex (see Fig. 7.25) into the northwestern part of the kabupaten.

In a broad sense the structural geology of the region is relatively simple, yet in detail is rather complicated. With reference to Fig. 7.26 three major geological elements can be identified:

1) the Late Pliocene-Lower Pleistocene low-angle upthrust fault, exposed in the southeastern part, extends towards the west underneath the cone of Ciremai. West of Ciremai, near the town of Tomo, the fault again becomes visible and trends further towards kabupaten Cirebon. This upthrust zone is characteristic for structural zone II (see Fig 4.3);
2) the Kromong complex which represents the uplifted and eroded remnants of a magma chamber of a Lower Pleistocene volcano;
3) the Middle Pleistocene to Holocene volcano Ciremai with its impressive cone loaded on a basement of plastic fine-grained strata.

The Kromong complex and the adjacent outcrops of Lower to Middle Pliocene claystones of the Kaliwangu Formation are somewhat unusual on this northern side of the regional upthrust fault which coincides with the hinge zone between the uplifted central part of Java and the adjacent Quaternary sedimentary basins. In the kabupatens described so far, the Tertiary basement has subsided considerably along sets of normal faults in the hinge zone and hence outcrops of Tertiary rocks north of the hinge zone are rarely found. The shape of the outcrops of the Kaliwangu claystones suggests a structural relation with the Kromong complex.

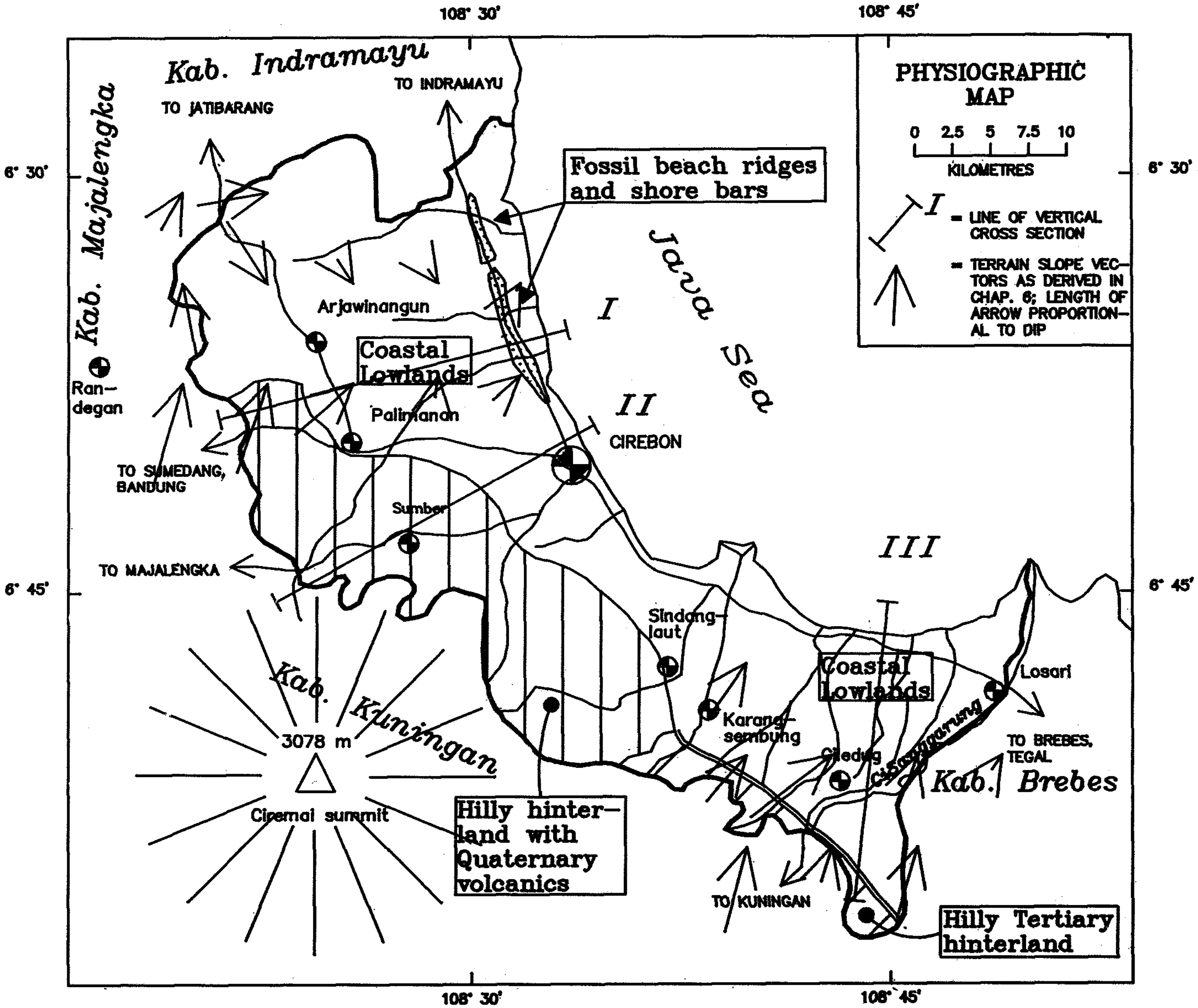


Fig. 7.25 General physical setting in kabupaten Cirebon.

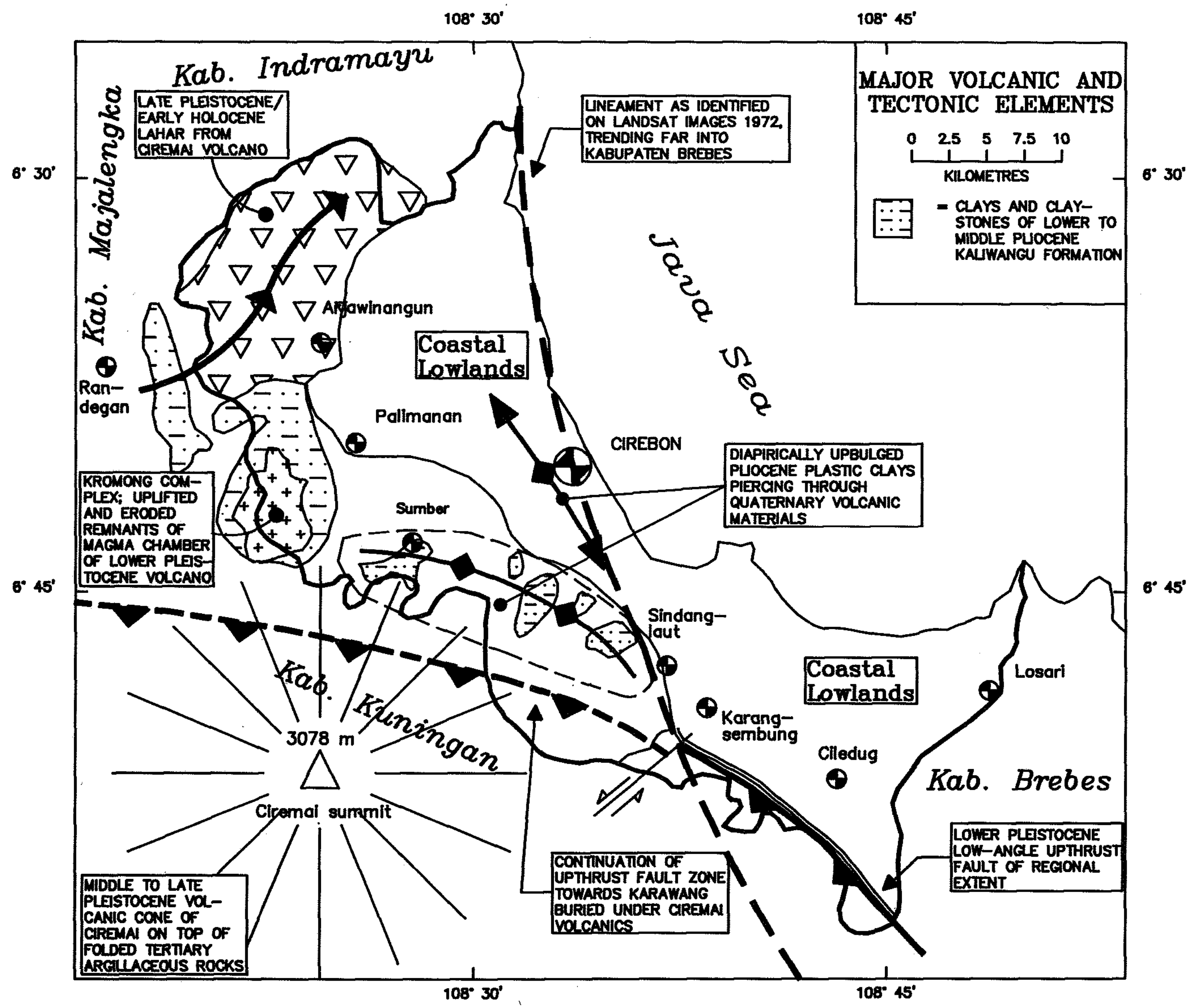


Fig. 7.26 The principal geological elements in kabupaten Cirebon.

A major uplift of the central geanticline of Java must have taken place prior to the outburst of regional volcanism in the arc. During this uplift phase the Kromong complex may have also been affected resulting in erosion of the original cone. The complex in fact may have acted as a rigid block resisting subsequent normal faulting and subsidence movements in the major hinge zone of the Quaternary sedimentary basins. This surmised structural behaviour may have led to the present situation of a high block on the northern side of the major hinge zone. The peculiarity of the structure and its continuation to deeper stratigraphic levels is perhaps reflected in the significant oil discovery in the Randengan Field in 1972, about 8 km NW of the Kromong complex (Soetomo & Sujanto, 1978), thus situated more or less on the crest of the N-S trending antiform structure. Oil in the Randegan Field is produced from Lower-Middle Miocene tuffaceous sandstones.

The presence of the impressive cone of Ciremai volcano and its effect on the underlying incompetent clayey strata are structurally expressed in the diapirically upbulged northeastern foot. The concave shapes of the northeastern slopes are likewise suggestive of diapiric movements. Clays of the Kaliwangu and Kalibiuk Formation are still being squeezed through the overlying covers of volcanic materials. In the field these clays give the impression of continuous creeping movements, induced by tectonic stress. Similar features are also found on the western slopes of Ciremai volcano.

A lineament visible with the naked eye on the 1972 LANDSAT images runs from the coastline, north of the town of Cirebon, far into the kabupaten Brebes and evidently crosses the river Cisanggarung. Whether important movements have occurred along the lineament could not be ascertained in the field. Nevertheless, this lineament with the characteristic shape of a normal fault fits well into the regional tectonics at the boundary between structural zones II and III. The sinistral wrench fault near Karangsembung might be related to the same feature.

7.7.2 *General groundwater setting*

The general groundwater setting in the coastal lowlands of kabupaten Cirebon is obviously controlled by the geological structure. The upbulged northeastern foot of Ciremai volcano appears to continue beneath the very narrow strip of coastal lowlands, giving rise to a diapiric ridge which separates groundwater basins in the north and east of kabupaten Cirebon. Deep and shallow groundwater in the lowlands, from the town of Cirebon to the boundary with kabupaten Indramayu, exhibits the same highly saline characteristics as found in the Cimanuk delta and adjacent areas. All deep well drilling efforts in the area at the beginning of this century again turned out to be failures. In 1897 a bore hole near Arjawinangun (Nr. 264 of the drilling archives of the Geological Survey in Bandung) reached a depth of 350 m without encountering any sand layers and producing only highly saline groundwater. From the poor lithological description the present author interprets that the Pliocene Kaliwangu clays have been reached at a depth of about 60 m. Another borehole (GSI archive nr. 554, 1909) near Palimanan has been drilled down to 183 m with the same results of highly saline waters and no sand layers. A third drilling in 1909 near the present coast and administrative boundary with kabupaten Indramayu yielded groundwater with a Cl^- content of 1,875 mg/l.

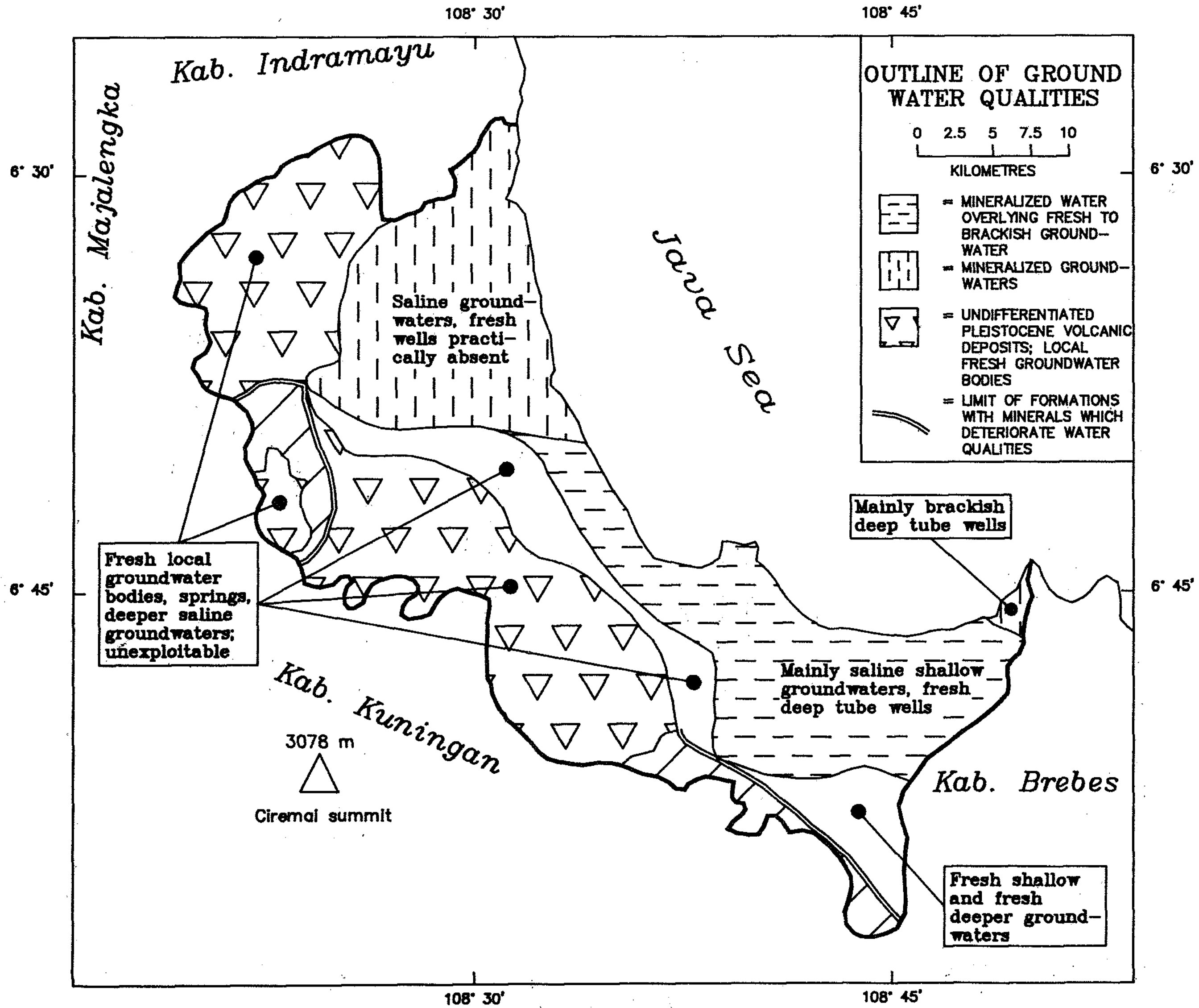


Fig. 7.27 Division of kabupaten Cirebon into major groundwater provinces.

Attempts in recent years by industries near Palimanan have rendered similar negative results. During the field surveys in 1983 and 1984 no deep wells were found in this area north of the road Cirebon-Palimanan, though some very shallow fresh groundwater bodies are present in the end lobes of the giant lahar flow in the northwestern part of the kabupaten. Groundwaters from layers under the lahar flow show the same salinities as found in the lowlands adjacent to the coast.

The permeable volcanic materials of Pleistocene and Early Holocene age at the southern side of the road Cirebon-Palimanan constitute well-circulated good aquifers for shallow groundwaters. Domestic water supply is easily obtained from dug wells and even from small springs in the deeper incised valleys. Poor quality groundwaters are found only in areas in which the diapirically deformed Pliocene marine clayey strata are exposed.

In the eastern part of the kabupaten, beyond the line Astanajapura-Sindanglaut, normal groundwater basin settings reappear with fresh groundwaters both at shallow and deeper levels. These groundwater basins extend further to the east into kabupatens Brebes and Tegal.

7.7.3 *Hydrochemical cross sections through kabupaten Cirebon*

An E-W cross section through the coastal lowlands in the northern parts of kabupaten Cirebon is shown in Fig. 7.28. As previously stressed, no deep tube wells were found during the 1984 surveys of the area. The only source of information on the possible configuration of the base of the Quaternary system is provided by a poor lithological description of the old GSI borehole nr. 264. It appears from this log that the Kaliwangu clays are found at a depth of about 60 m under the town of Arjawinangun, which seems plausible. However, the description is somewhat contradictory to the hydrogeological report which states that suitable water-transmitting layers are absent. From about 30 to 60 m 'yellow tuffaceous sandstones' are mentioned in the log, overlain by a 'red hard clay'. The tuffaceous sandstones may coincide with the Middle Pleistocene Gintung Formation, consisting mainly of reworked volcanoclasts and erosion materials from older Tertiary formations. The red hard clay is thought to be a paleosol on top of the Gintung Formation. As will become apparent in the next cross section, situated further to the south, the Gintung Formation is to be expected in this Cirebon section I.

Whether the Gintung Formation directly overlies the Kaliwangu clays remains uncertain and volcanics of the old Kromong volcano can be expected to be intercalated. Nevertheless, on geological grounds the Gintung Formation may well be present in cross section Cirebon I and is anticipated to pinch out further to the north. Thus the old borehole descriptions are erroneous in the sense that although the penetrated groundwaters may well be highly saline, suitable aquifer horizons could still be present. Although the configuration in an easterly direction is totally unknown a series of en-échelon faults is expected on this side of the Kromong complex structure. A normal fault can thus be expected between the old abandoned well Nr. GSI 264 and the first outcrops of the Kaliwangu claystones and in all likelihood a second fault coinciding with the lineament parallel to the coastline.

Brackish to salt groundwaters of the NaCl type are tapped in the coastal lowland deposits.

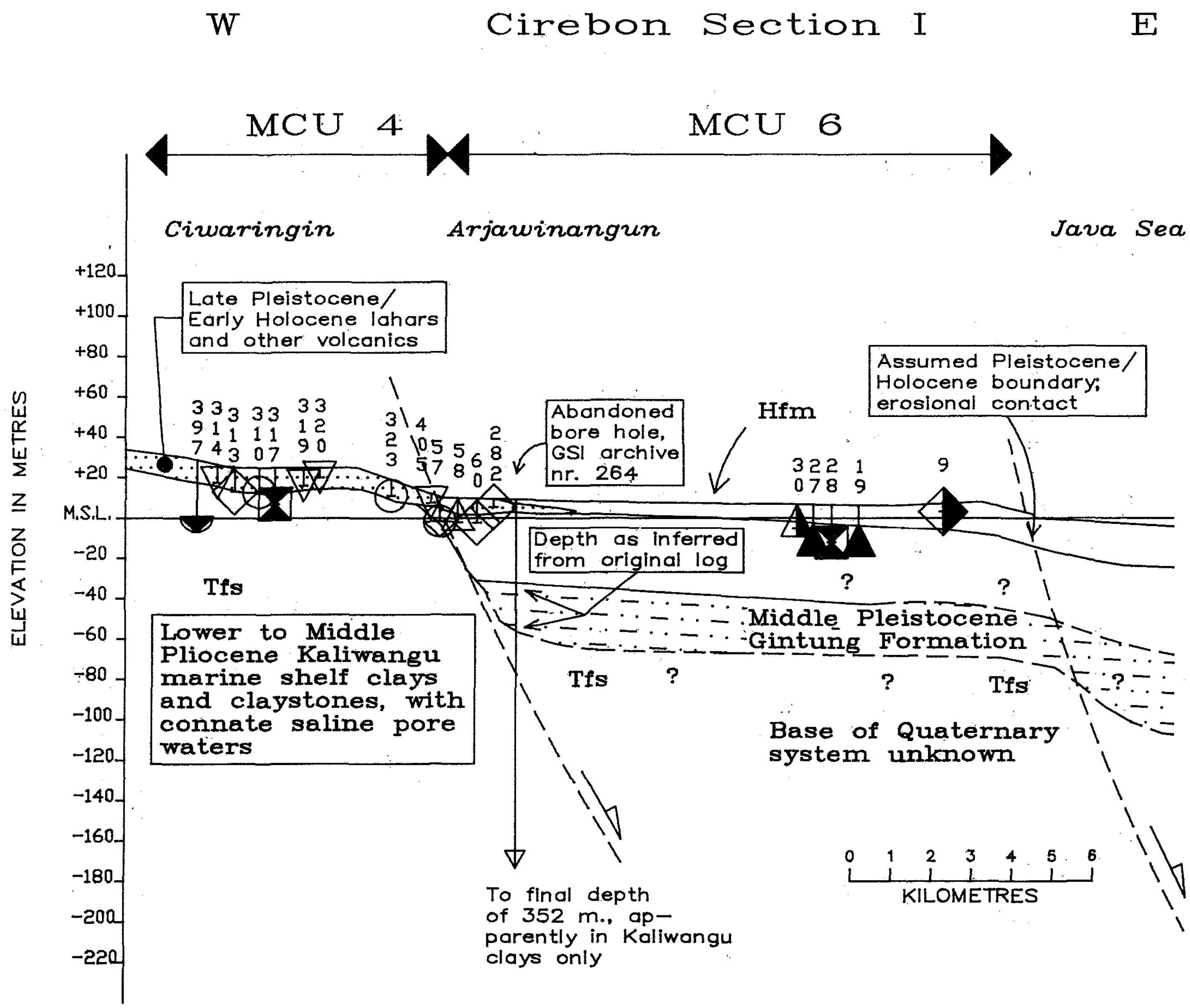


Fig. 7.28 Hydrochemical cross section Cirebon I (see Fig. 7.5 for general legend).

Thin groundwater lenses occur in the fossil beach ridge deposits upon which the road Cirebon-Indramayu is built, with locally fresh to brackish NaCl to NaMix types such as in dug well nr. 9. Depending on well depths, fresh $CaHCO_3$ and $MgHCO_3$ water types are found in the Late Pleistocene to Early Holocene lahar and reworked volcanoclastic deposits draped over the exposed Kaliwangu claystones. Slightly deeper wells touching the claystones exhibit fresh NaMix to brackish NaCl types. This situation continues to the west where the claystones are covered by a veneer of the giant lahar flow. Tube wells drilled into the claystones yield groundwaters with electrical conductivity values of 3,710 and 3,950 μmhos/cm in the case of wells nr. 317 and 397. Well nr. 397 is owned by the tile factory P.T. Terra Cotta located near Ciwaringin in the Kaliwangu claystones. Two other deep wells are reported to have been drilled to depths of 60 and 130 m without positive result.

An interesting aspect of section Cirebon I is the fact that although a slightly elevated topography is formed by the giant lahar flow, groundwater flow systems which could have been driven by this easterly directed terrain slope are not likely to occur in the present geological situation. This is due to the underlying Kaliwangu clays which will hamper any deeper flow systems. This case illustrates that a volcanogenic fan and lahar deposit which introduce a topography with a substantially higher terrain slope than found in the coastal lowlands, may not always generate a deeper groundwater flow system when the underlying strata are practically impervious.

A different geological situation is met in cross section Cirebon II. The geological structure is not easily deciphered in this section without the clues provided by a most peculiar small isolated hill at Klayan, along the road Cirebon-Indramayu at about 4 km to the north of the town of Cirebon. The significance of this small hill was discussed in Chapter IV, in which it was described as being built up of horizontally bedded reddish weathered volcanic breccias and conglomerates from the Gintung Formation. None of the geological descriptions available to the present author mention the small hill. The typical reddish weathered volcanoclastic materials with ferro-manganese staining and the fact that chemical rotting of most boulders has progressed to such a stage that only friable clayey materials remain, are usually strong indications of the Gintung Formation. The hill is located too far from the Middle Pleistocene eruption centre of Ciremai volcano to speculate on the possibility of it being a remnant volcanic ruin. The top of the hill fits into a planation level at about 20 m altitude which is present in the Gintung volcanoclasts along the southwestern border of the narrow coastal lowland strip south of the town of Cirebon. A continuation of that level may be present to the southwest along the cross section though buried by the younger volcanic deposits of Ciremai. The eastern flank of the hill displays evident signs of marine abrasion, similar to the fault-bordered planation surfaces with marine abrasion features found west of Semarang, near Weleri. During the higher Holocene sea levels of 4 to 6 m above present level the hill must have been a small island. In the present situation the hill is surrounded by Holocene marine clays overlain by flood plain deposits. From a structural viewpoint Klayan hill is probably related to the second diapiric upbulging depicted in Fig. 7.29. The structure may be visualized as a tilted slab of Gintung Formation, resulting from the underlying diapir in the Kaliwangu and Kalibiuk clays. In this model Klayan hill thus represents the exposed upper edge of a slab which later experienced planation surface formation during drier climatic conditions.

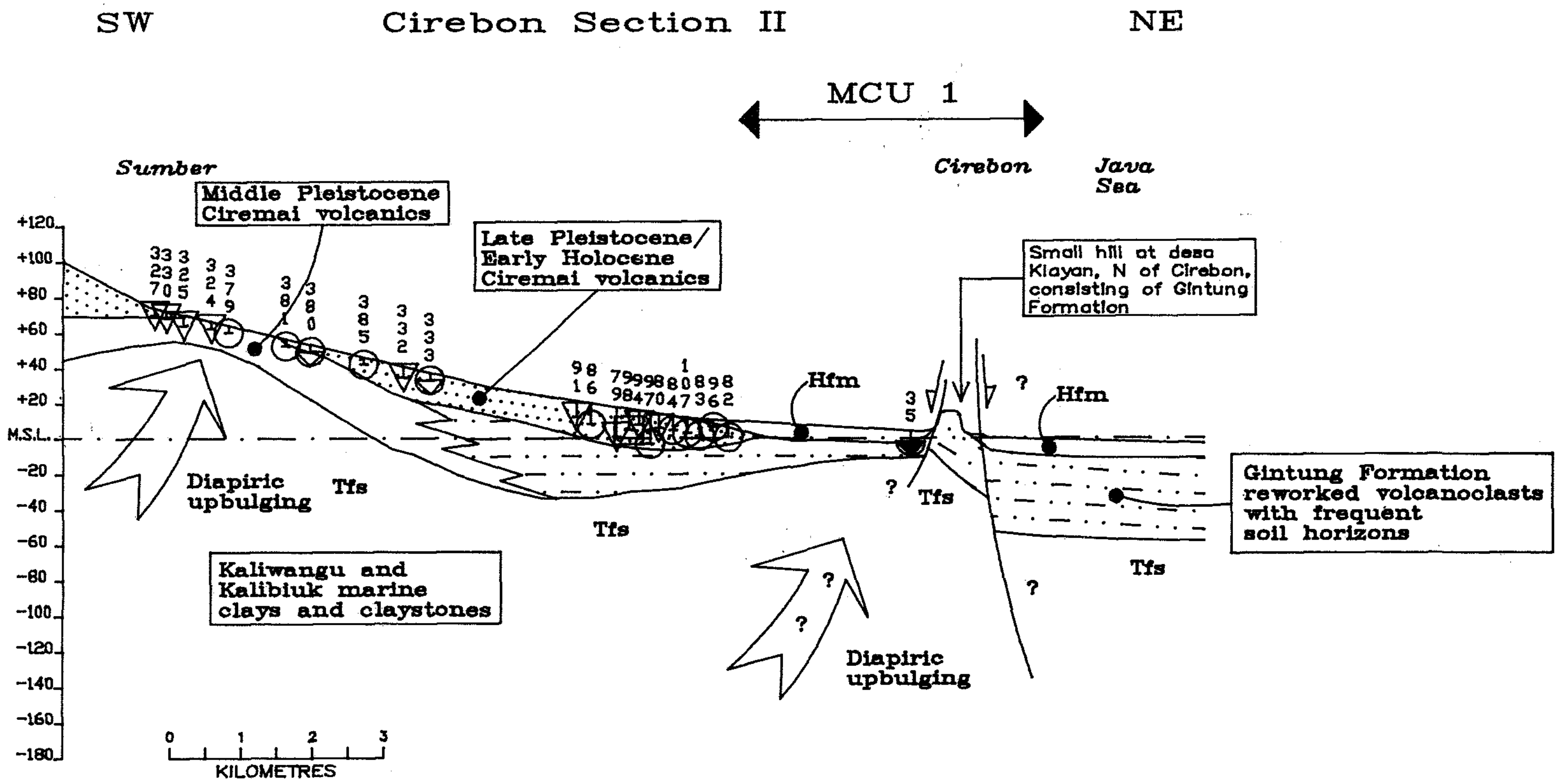


Fig. 7.29 Hydrochemical cross section Cirebon II (see Fig. 7.5 for general legend).

The significance of the hill is threefold: (a) the Gintung Formation must be present at shallow depths and veneered only by Holocene deposits; (b) the Gintung deposits are also present further to the SW along the section line, though overlain by younger volcanic blankets of Ciremai volcano; and (c) the Gintung deposits are probably present in cross section Cirebon I. The remaining part of the geological structure in section Cirebon II is conjectural with respect to thicknesses and positions of the diapiric upbulges, though the diapiric structure in the southwest can be readily observed from the surface geology. Nevertheless, this geological configuration accords with the presence of the Gintung Formation at shallow depths and the absence of deep wells in the coastal lowlands.

The hydrogeological data in this cross section are unfortunately limited to shallow groundwaters. A strong contrast can be noticed between the chemical qualities of groundwaters in the coastal lowlands and those in the well-flushed volcanic materials of Ciremai. The latter are invariably characterized by fresh $CaHCO_3$ and $MgHCO_3$ types. An exception may be tube well nr. 98 with a depth of 12 m, $NaHCO_3$ type of groundwater and a low pH value which suggests the Gintung deposits as aquifer materials. Analogous to cross section I, if Kaliwangu and Kalibiuk beds are found at shallow depths in section Cirebon II, then the effect of the hilly topography on Ciremai volcanoclasts with respect to creating a deeper groundwater flow system may be counteracted by the impervious substratum.

Cross section Cirebon III (see Fig. 7.30) is situated in the eastern part of kabupaten Cirebon in which the Quaternary sedimentary basin fill is again expected to become thicker away from the diapiric upwarps of the Ciremai structures. Near the town Astanajapura deep wells occur again tapping the exploitable deeper groundwater resources which continue into the neighbouring kabupaten Brebes. Except for the older colonial deep wells and some deep tube wells in the flat area of Cisanggarung delta, deep wells in this part of kabupaten Cirebon generally yield fresh groundwaters.

The geological structure along section Cirebon III is conjectural, in particular the thickness and position of the Gintung Formation, and is in fact based on information gained from the lithological log of the IWACO deep well at Waled (deep well for piped water supply of district town (IKK) Waled). This deep well situated about one kilometre north of the outcropping Pliocene formations reaches a depth of 120 m and according to the drill log penetrates mainly volcanic deposits. The final depth may well correspond with the top of the Cijulang Formation, though the lithological description of the borehole is too poor to draw firm conclusions. Another hint which suggests the presence of the Gintung Formation in the underground is the chemical type of deep tube wells in this section. These hydrochemical types differ significantly from the characteristic fresh $NaHCO_3$ types with high pH values, resulting from cation exchange processes, as found in the deeper levels of the kabupatens discussed so far. It stands to reason that the Gintung Formation will be present in the subsurface in this part of kabupaten Cirebon since it outcrops along the entire southern administrative border. Furthermore, the sedimentology of the formation gives the impression of an environment with shallow braided meandering rivers, sheet flood deposits, lahars and airborne ash tuffs, all suggesting large fan-shaped geometries.

The most interesting feature of cross section Cirebon III, however, is the substantially higher terrain slope as compared to sections in the previously discussed kabupatens. The effect of the terrain slope can be noticed in both the groundwater flow pattern and the hydrochemistry. This section shows a broad strip of coastal lowland acting as recharge area, with descending stream lines, and vice versa a very narrow belt in which the streamlines ascend to the surface.

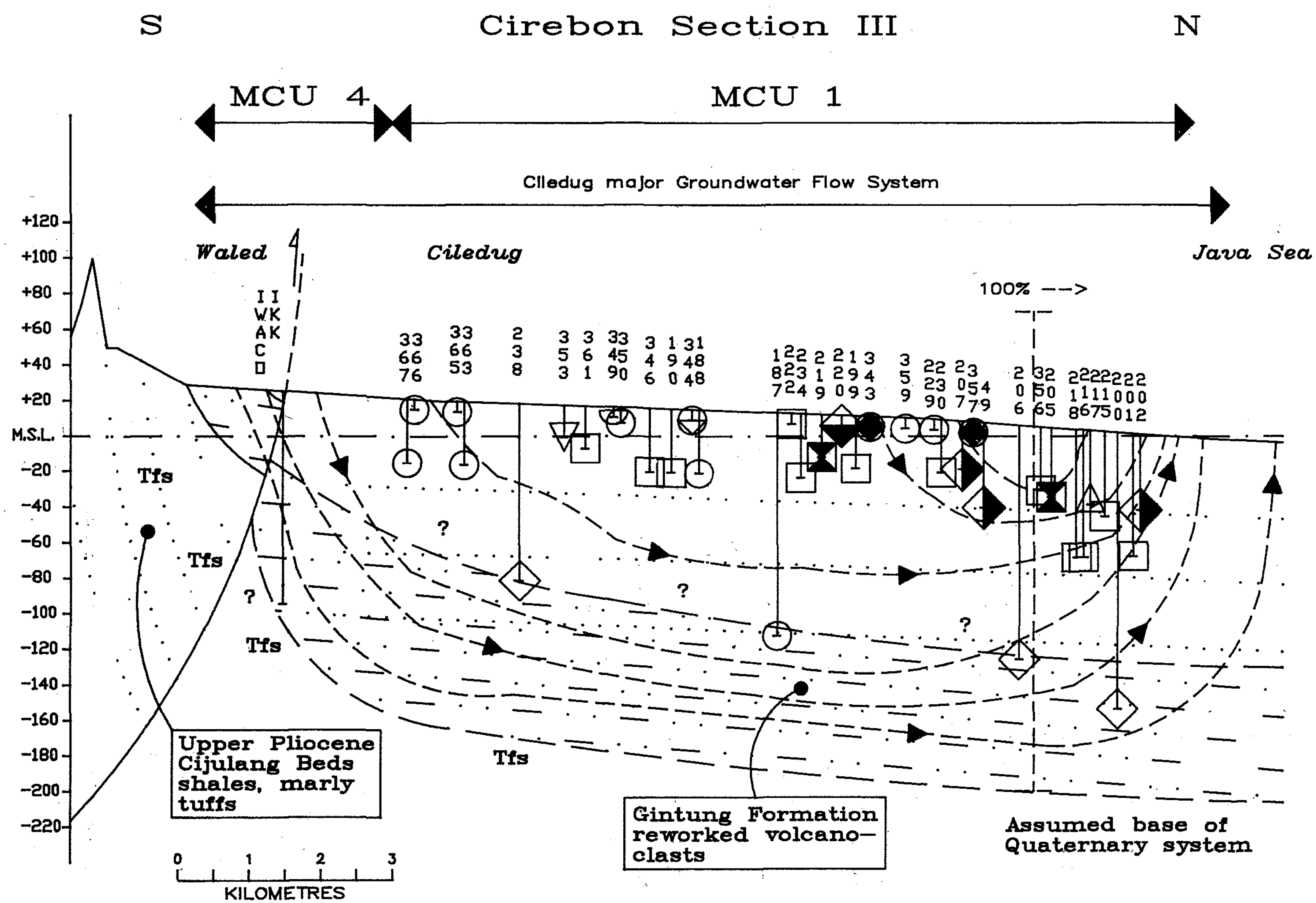


Fig. 7.30 Hydrochemical cross section Cirebon III (see Fig. 7.5 for general legend).

This pattern differs from the flow settings in the previous cross sections, in which the discharge areas largely dominate in the coastal lowlands and where the main infiltration areas for groundwater flow systems occupy only the southern parts of the sections. Thus the Ciledug Groundwater Flow System in this part of kabupaten Cirebon appears to cover the entire cross section through the coastal lowlands. In the flow model configuration shown in Fig. 7.30 the hydraulic conductivities of the Gintung Formation are assumed to be 1.0 and 0.01 m/day for K_h and K_v respectively, equal to the Late Pleistocene Volcanic Fan Formation in West Java kabupatens. The total groundwater flux is determined as 0.44 m^2/day in this configuration.

The hydrochemistry and chemical types agree with the setting of a groundwater system taking up the entire cross section. Since the larger part of the section acts as a recharge area, an active process of fresh groundwater flushing can be expected. This is reflected in the abundance of F- to f-class salinities. Noteworthy is the abundance of F2-$NaHCO_3$+ chemical types for tube wells with depths up to 50 m. Even the deep tube wells nr. 200 and 206 show only 66 and 76 mg/l Cl^- in their respective chemical analyses. The shallow phreatic groundwaters are likewise predominantly fresh with a tendency to $CaHCO_3$ types, though this might be partly due to the nature of suspended sediment loads from non-marine sources in the Cisanggarung river. Large areas of the Cisanggarung catchment are covered by thick young volcanoclastic deposits of Ciremai volcano and the Gintung Formation is also widely exposed. The setting found along cross section Cirebon III applies only to sections in inter-deltaic areas; slightly further to the east in the flat Holocene-built Cisanggarung delta, the typical brackish f- to b-class NaCl types of groundwater reappear in deeper tube wells.

7.7.4 *Conclusions on the hydrogeology in kabupaten Cirebon*

With respect to kabupaten Cirebon the following conclusions can be drawn:

1) the potential effect of the giant lahar flow from Ciremai volcano in generating a groundwater flow system in the northern coastal lowlands of kabupaten Cirebon is largely impeded by the substratum which consists of practically impervious Kaliwangu claystones. Hydrogeologically, the presence of the lahar flow in the subsoil is noticeable merely by local thin fresh phreatic groundwater bodies;
2) the hilly to mountainous topography associated with Quaternary volcanogenic deposits on the northeastern foot of Ciremai volcano is likewise unable to generate a deeper groundwater flow in the coastal lowlands, due to the underlying practically impervious beds of the Kaliwangu and Kalibiuk Formations;
3) those parts of the eastern groundwater basin in kabupaten Cirebon beneath the morphological unit 1 (MCU 1) are well flushed by a groundwater system which occupies the entire N-S cross section. The Holocene-built young deltaic areas belonging to morphological unit 6, such as the Cisanggarung, and in particular future progradations of these deltas will become increasingly uncoupled from this important sub-regional groundwater system. Future progradations will face the same fate of unflushed brackish to salt deeper groundwaters as observed for the Citarum and Cimanuk deltas;

4) the hydrogeology of kabupaten Cirebon is strongly influenced by the subsidence of Ciremai volcano, giving rise to diapiric structures of practically impervious claystones. Another important structural effect on groundwater systems in the coastal lowlands appears to be the Kromong complex, which acted as a rigid block counteracting subsidence and caused the antiformal structure in the Kaliwangu Formation north of the tectonic hinge zone.

7.8 *Kabupatens Brebes and Tegal (Central Java)*

7.8.1 *Introduction*

The final two kabupatens to be described in this section are taken together for several reasons. The principal reason is the special geological setting in both kabupatens, which ignores administrative boundaries and should be considered in its entirety. Another reason is the fact that these two kabupatens have not been surveyed by the present author to such an extent as in West Java. Well surveying in kabupatens Brebes and Tegal was conducted in 1986 and 1987 by hydrology student teams from the Gadjah Mada University, Yogyakarta in cooperation with students from the Free University, Amsterdam. The hydrogeological cross sections to be presented in this section are therefore entirely based on raw well data collected by the student survey teams. Instead of executing systematic well surveys, much attention has been given by the author to the geological structures adjacent to the southern periphery of the coastal lowlands.

The hydrogeological cross sections have been limited to three and include the most important geological structures to be found in the boundary coastal lowlands and hinterland.

7.8.2 *General physical setting*

The kabupaten of Brebes occupies an area of 1,658 km^2 and due to the elongated catchment of the river Kali Pemali extends far into the central volcanic arc. The kabupaten of Tegal on the contrary is much smaller, with an area of 902 km^2 and located on the northern flanks of the impressive Slamet volcano.

The constricted strip of coastal lowlands found in the eastern part of kabupaten Cirebon further widens to the east in kabupaten Brebes. At the boundary between Brebes and Tegal the lowlands abut the enormous volcanic fan of Balapulang. Further to east in kabupaten Tegal the coastal lowlands narrow to a width of only 8 km along the northern deformed flank of Slamet volcano. The southern periphery of the coastal lowlands exhibit the common distinct break of slope at the contact with the Tertiary fine-grained argillaceous hinterlands. An outstanding geomorphological feature is the enormous Balapulang volcanic fan with its highly symmetrical shape and radial drainage pattern. The radius of the fan is about 20 km, before the tuffaceous sandstones become completely overlain by younger Holocene deposits.

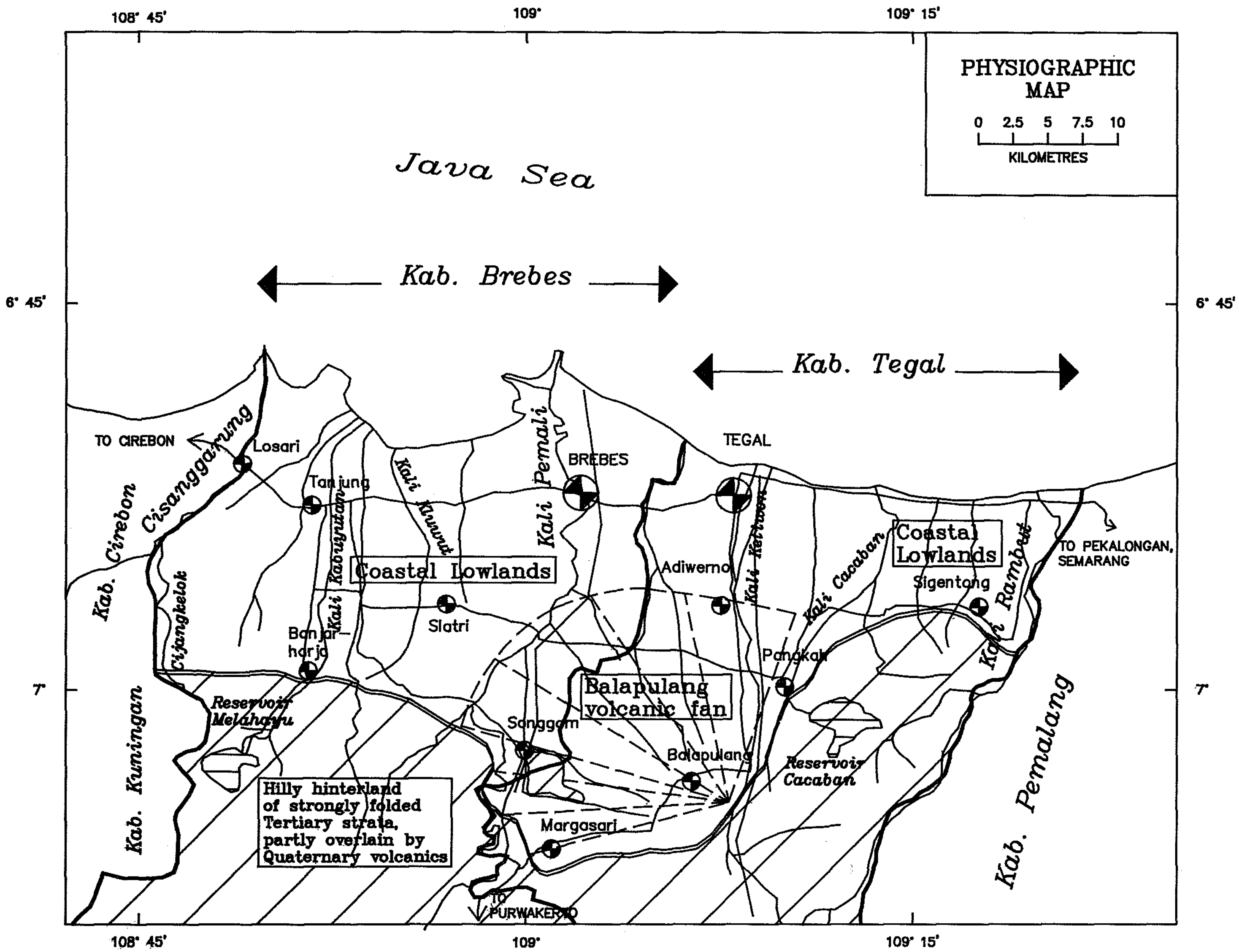


Fig. 7.31 General physical setting in kabupatens Brebes and Tegal.

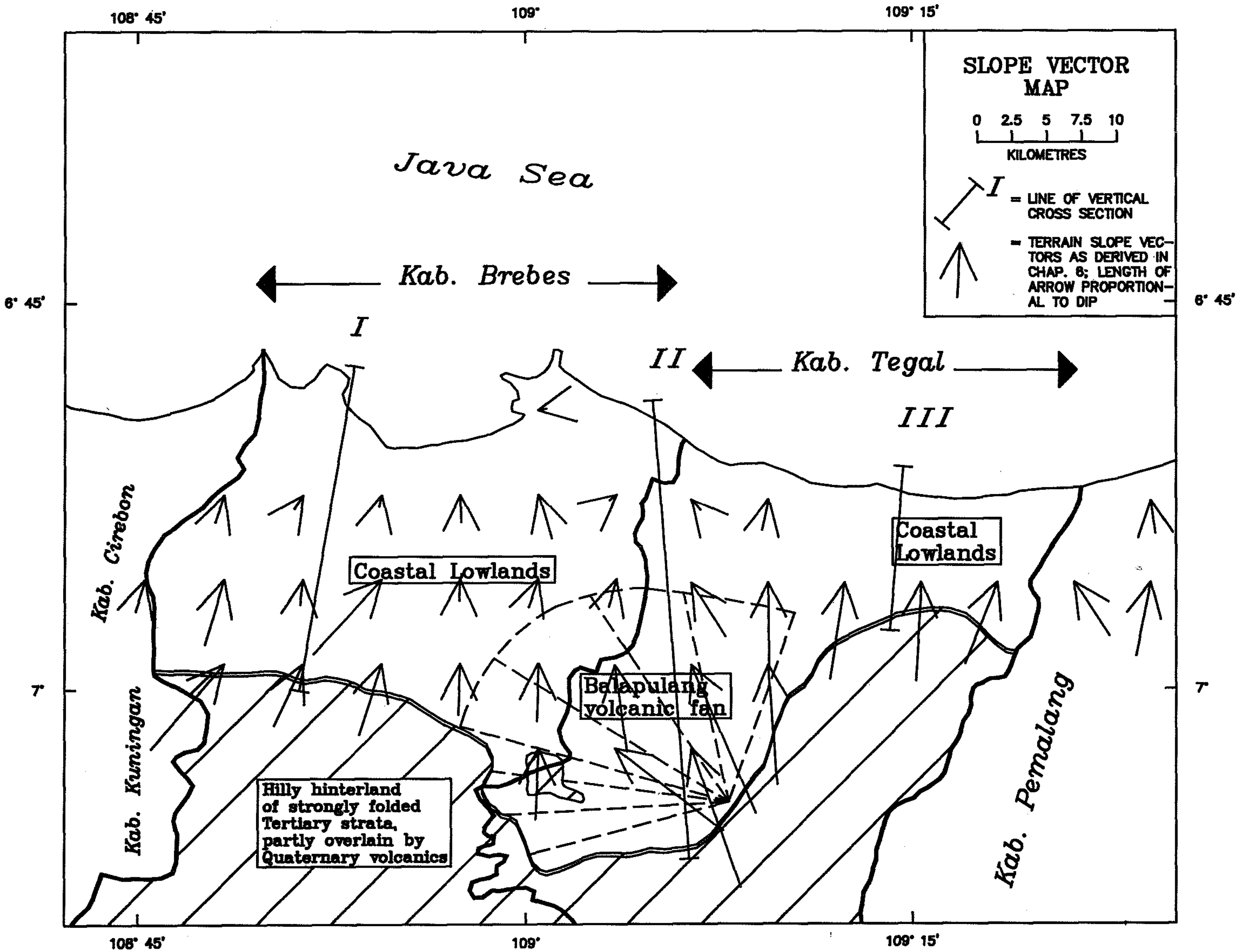


Fig. 7.32 Terrain slope vectors (derived in Chapter VI) in kabupatens Brebes and Tegal.

The apex of the fan reaches an altitude of 300 m. All the material of the Balapulang fan originated from the vent of Slamet volcano and must have been supplied through the present-day largely buried valley, most likely a graben structure, SE of the village Balapulang. The geology of the Balapulang fan was described in section 4.2.3. Apart from the spectacular shape of the fan, the hydrogeological significance and, as will become apparent in the following sections, also the widespread effect on groundwater flow justifies a joint discussion of these two kabupatens.

Volcanic materials from Slamet volcano which reached the coastal lowlands are not restricted to the Balapulang fan only. On the eastern side of the Tegal/Pemalang kabupaten boundary a similar fan of volcanoclasts occurs, with volcanic materials finding their way to the coastal lowlands via the larger rivers such as Kali Cacaban and Kali Rambut.

At the eastern side of the Balapulang fan the Tertiary hinterland exhibits a strongly protruding arc-shaped boundary line around the huge Slamet volcano, resulting in a narrow coastal lowland strip of only 8 km wide. The major fold trends in this Tertiary hinterland also appear to be arranged in an orderly fashion around the northwestern foot of the Slamet cone.

Large rivers with their headwaters as distant as the central volcanic arc are the Cisanggarung, discussed in a previous section on kabupaten Cirebon, and the Kali Pemali which originates on the southwestern slope of Slamet cone. A rapidly prograding delta is being built up by the river Kali Pemali, near Brebes. Smaller rivers without significant delta building are the Kali Kabuyutan and Kali Kluwut in kabupaten Brebes with their catchments in the folded Tertiary fine-grained argillaceous rocks. In kabupaten Tegal rivers draining major parts of the northern flanks of the Slamet volcano are the Kali Ketiwon, Kali Cacaban and Kali Rambut.

Major differences exist between coastal lowlands in the West Java kabupatens discussed so far and the lowlands in east Cirebon, Brebes and Tegal. These differences can be summarized as follows:

1) the Late Pleistocene Volcanic Fan Formation, which occupies vast lowland areas in Karawang, Subang and Indramayu, is absent in Brebes and Tegal;
2) major tectonic differences occur in Brebes and Tegal where the long Plio-Pleistocene thrust belt as found in West Java terminates and abuts an arc of folds around Slamet volcano;
3) the Lower Pleistocene Gintung Formation of reworked volcanoclasts, although presumably not present in Indramayu and Subang but important in Cirebon, rapidly thins in an easterly direction and is absent in the eastern part of Brebes and Tegal;
4) important new morphological elements, such as the enormous volcanic fans, are found in the areas of Brebes and Tegal.

The map shown in Fig. 7.31 summarizes the most important physiographical aspects of kabupatens Brebes and Tegal. In order to avoid too many features and symbols on the map in Fig. 7.31, the fairly high number of slope vectors for grid cells measuring 6 km are shown on a separate map in Fig. 7.32. The radial shape of the Balapulang fan is well expressed in the vector orientations, which was also concluded from the statistical analysis (see Chapter VI) in which the Balapulang fan emerged as a distinct morphological unit (MCU 5).

7.8.3 *Major tectonic structures*

Proposed above and discussed in Chapter IV within the framework of regional tectonics (see Fig. 4.3), drastic tectonic changes are found in a W to E direction in the kabupatens Brebes and Tegal. In the western part of Brebes the common upthrust belt, trending from West Java under the Ciremai volcano complex, is still present along the southern periphery of the coastal lowlands. The same tectonic styles are retained of open synclines and tightly folded anticlines which become increasingly deformed towards the major hinge zone, with dipping axial planes accompanied by upthrust faults with southward dipping curved fault planes.

Approaching the Kali Pemali river the axial trend lines of the fold bundles and fault lines of the numerous upthrust faults curve clockwise from an initial E-W direction to an almost N-S direction. Complicated structures are found in the valley of the river Kali Pemali where even the Lower Pleistocene Gintung and Mengger Formation are tightly folded. East of the Kali Pemali valley the bundles of folds are arranged in arcs apparently around the toes of the Slamet cone, in particular around the northeastern and eastern foot. Large transverse faults are present, controlling the courses of many rivers such as the Kali Cacaban and the Kali Rambut with mainly strike-slip movements.

The dislocations along these long transverse wrench faults may differ considerably due to the incompetent behaviour of the Tertiary rocks composed of mudstones, marls and shales. In addition to these long transverse faults many shorter faults are found with their fault planes parallel to the long ones. Fig. 4.1 shows not only a number of these shorter transverse faults but also the geology as remapped by the present author for a part of the hinterlands in Tegal. Although hard to trace in the field in these incompetent rocks, dislocations along tuffaceous sandstone beds may yield some clues such as occasional salt water seeps and minor folds associated with shearing stresses. These plunging folds which occur in groups with more or less parallel alignment of their axes, in which the axes intersect the fault line at a sharp angle, have been found along the river Kali Rambut near Gongseng (see also Fig. 4.1).

The general picture gained from the pattern of folds and thrust faults dissected by the long transverse faults along this northeastern and eastern foot of Slamet volcano, is one of gravity-induced outward gliding sectors triggered by a major collapse of the Middle Pleistocene Cowet volcano, which predated the present Slamet cone. Based on micro-tectonic features at the scale of an outcrop, such as the fresh looking slickensides, backwardly rotated fluvial terraces and the complaints of the local inhabitants of unstable fields (tanah gerak), the impression is gained of a generally continuous process of gravitational gliding and deformation.

Near the apex of the Balapulang volcanic fan a graben structure is thought to be present which must have been formed by stretching forces due to outward gliding movements north of the graben. Hot springs have been found along the fault lines. The existence of the graben structure may then also explain the position of the Balapulang fan, since the volcanoclastic materials of the fan must have been channelled through the structure, thereby securing the fan apex position.

The significance of these gravitational gliding structures for the coastal lowlands is their assumed front, which in all likelihood continues far under the Upper Pleistocene and Holocene cover.

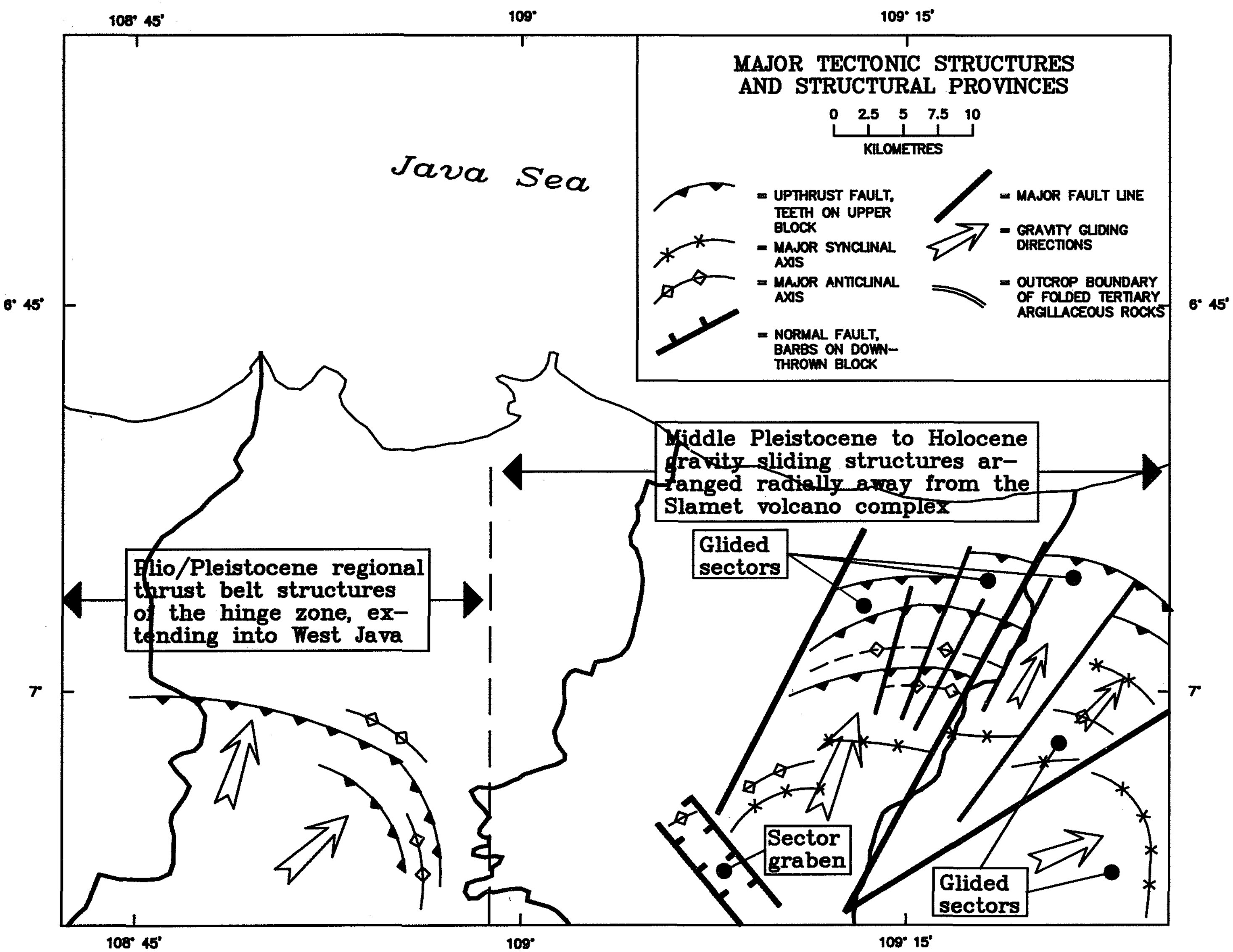


Fig. 7.33 Major tectonic structures in kabupatens Brebes and Tegal.

Based on the patterns on the geological map of the area (Djuri, 1975, Quadrangle Purwokerto-Tegal, scale 1:50,000) and the intensity of deformation in Pliocene outcrops in the hilly hinterland bordering the lowlands, far-reaching lobes of the gliding structures can be expected. Another aspect of these more or less continuously gliding movements is the effect on the lowland piedmont plain. One may expect upthrusting and upbulging movements of the Pliocene strata beneath the coastal lowland cover. A glance at Fig. 6.4, which displays the slope vectors for each statistically discriminated group, shows that the vectors of group 5 (MCU 5) representing the Balapulang fan are also found in the piedmont plain of the coastal lowlands in Tegal. This may suggest still active thrust and gliding movements which give rise to high terrain slopes (about 3 m/km). On the other hand, as already shown in Fig. 4.1 with different positions of the anticline crests, one may expect the deformed Pliocene strata to occur at varying depths beneath the lowland, changing abruptly in depth as one of the shorter transverse faults is crossed.

7.8.4 General groundwater setting

Domestic water supply from groundwater resources is generally fairly problematical in both kabupatens Brebes and Tegal. Although kabupaten Tegal is somewhat better off than Brebes, due to the presence of the Balapulang fan, outside the fan area shallow groundwater resources are frequently highly mineralized even along the hinterland border, far from the present-day coastline (see Fig. 7.34). Sulphate and chloride contents in the coastal lowland flood plain clays may reach several grams per litre. Vast areas in Brebes are characterized by saline shallow and deep groundwaters.

There is a significant difference between these kabupatens and those in West Java; the omnipresent Late Pleistocene Volcanic Fan Formation in West Java is lacking in Brebes and Tegal. This volcanoclastic formation at present constitutes an erosional area and is being actively dissected. In contrast is the situation in Brebes and Tegal, by reason of the piedmont plains which, although incised by the larger rivers, are still accumulation areas for the clayey sediments derived from Tertiary source areas in the hinterland. A significant difference thus exists in distance from erosion- to accumulation areas in the West- and Central Java kabupatens; that for the latter is much shorter. Clayey and silty sediments derived by erosion from the Pliocene and Miocene marine strata and transported over short distances to the accumulation areas in the piedmont plains will most likely not be subjected to much alteration in original pore water composition. Consequently, the much longer transport systems found in the West Java coastal kabupatens may exert an effect on the pore water composition.

Although more or less the same type of Tertiary sediment lithologies are found in the West- and Central Java coastal kabupatens, such high sulphate and chloride contents in shallow groundwaters have not yet been met in West Java. The highly mineralized shallow groundwater resources in the piedmont plain belt of Brebes and Tegal are thus in sharp contrast with the fresh shallow groundwaters common to southern parts of the West Java coastal lowlands. These conspicuous and highly mineralized groundwaters without definite pattern lie far from the present-day coast, occur at altitudes which have never been reached by former sea levels in the geological past and will be discussed further below.

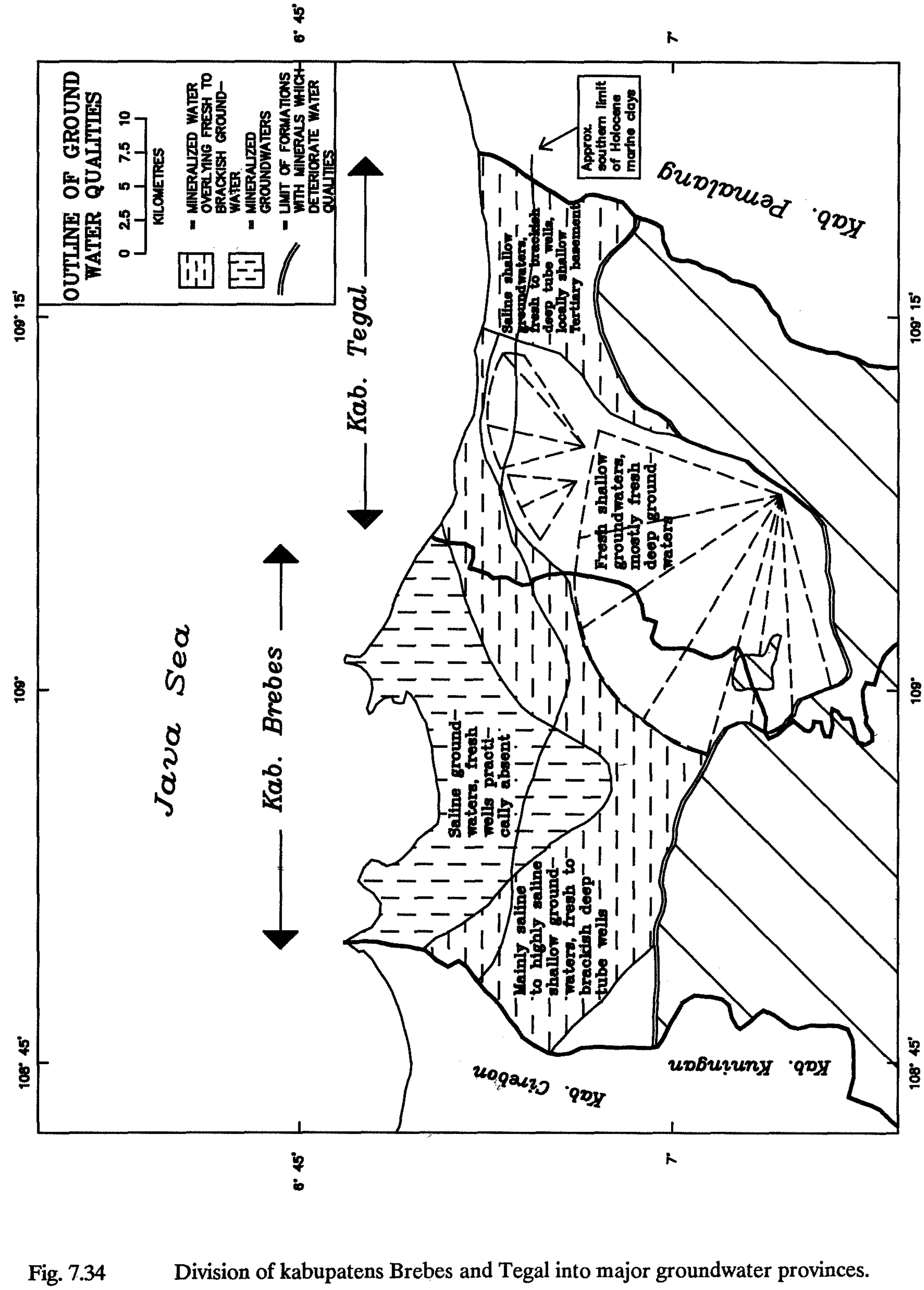


Fig. 7.34 Division of kabupatens Brebes and Tegal into major groundwater provinces.

The strip with brackish to salt deeper groundwaters, starting in the Cisanggarung delta in Cirebon, widens rapidly in kabupaten Brebes but narrows again in the vicinity of the endlobes of the Balapulang fan. The intercalated strip characterized by generally fresh deep groundwaters appears to run parallel to the outer shape of the fan. The impression is gained that the Balapulang fan constitutes an important morphological and topographical element capable of influencing deeper groundwater.

Reasonable shallow groundwater qualities with fresh $CaMgHCO_3$ types are found in the coarse fluvial materials NE of the Balapulang fan proper, made up of fan materials which have been reworked and redeposited by the river Kali Cacaban. Groundwater qualities in the Balapulang fan are invariably good, showing low-mineralized $CaHCO_3$ and $MgHCO_3$ types. Fresh shallow groundwaters are also present in areas underlain by the Lower Pleistocene Gintung Formation of reworked volcanoclasts, such as in the southwestern part of Brebes.

Based on the shallow dug well surveys the approximate southernmost extension of the Holocene shallow marine deposits under the coastal-deltaic plain association is shown in Fig. 7.34. The curving line around the Balapulang fan suggests the influence of the fan endlobes on the extension.

7.8.5 *Hydrochemical cross sections through kabupatens Brebes and Tegal*

The cross section Brebes/Tegal I geologically resembles section Cirebon III as one may expect the presence in the underground of the pervious Gintung Formation. The poor lithological description for test borehole LW63 from the Indonesian Department of Public Works suggests the presence of Gintung volcanoclasts. However, the analogy does not apply to the division into morphological zones; the low-angle coastal-deltaic plain belt (MCU 6) has a width of about 15 km and an average slope of only 0.4 m/km. The Holocene shallow marine clays deposited on the erosional land surface at the Pleistocene-Holocene boundary may extend to the south even beyond the small town of Tanjung, which illustrates the rate of Holocene coast accretion. Van Schaik (1986) states that before 1880 small seagoing vessels were still able to reach the village of Tanjung.

A number of tube wells in the town of Banjarharja tap saline groundwaters from the Miocene Halang Formation, consisting here of marine clays and mudstones. Even a large diameter 120 m deep abandoned well drilled at a distance of 3 km normal to the section still yields highly saline water. Table 7.15 lists the main chemical characteristics. Appendix II shows that the chemical composition of deep well 218 is close to that of average sea water. Since the sample was taken from the water column at the well collar, one may expect even higher salinities in the water column much deeper in the riser pipe.

The abrupt break of slope in the topography near Cigedog is noteworthy and may point to structural control. Another argument for structural control is the abrupt changes in depth of the deeper tube wells. Nevertheless, the Pliocene Kaliglagah Formation is thought to be present at shallow depth N of Banjarharja. Contrary to the geological mapping by Silitonga & Memed Masria (1978), the present author found the Kaliglagah Formation exposed just east of Banjarharja, near the villages Nambo and Gunungkarang. Old manuscripts and field reports of pre-war geological surveys (Ter Haar, 1930, 1932) make mention of Pliocene outcrops.

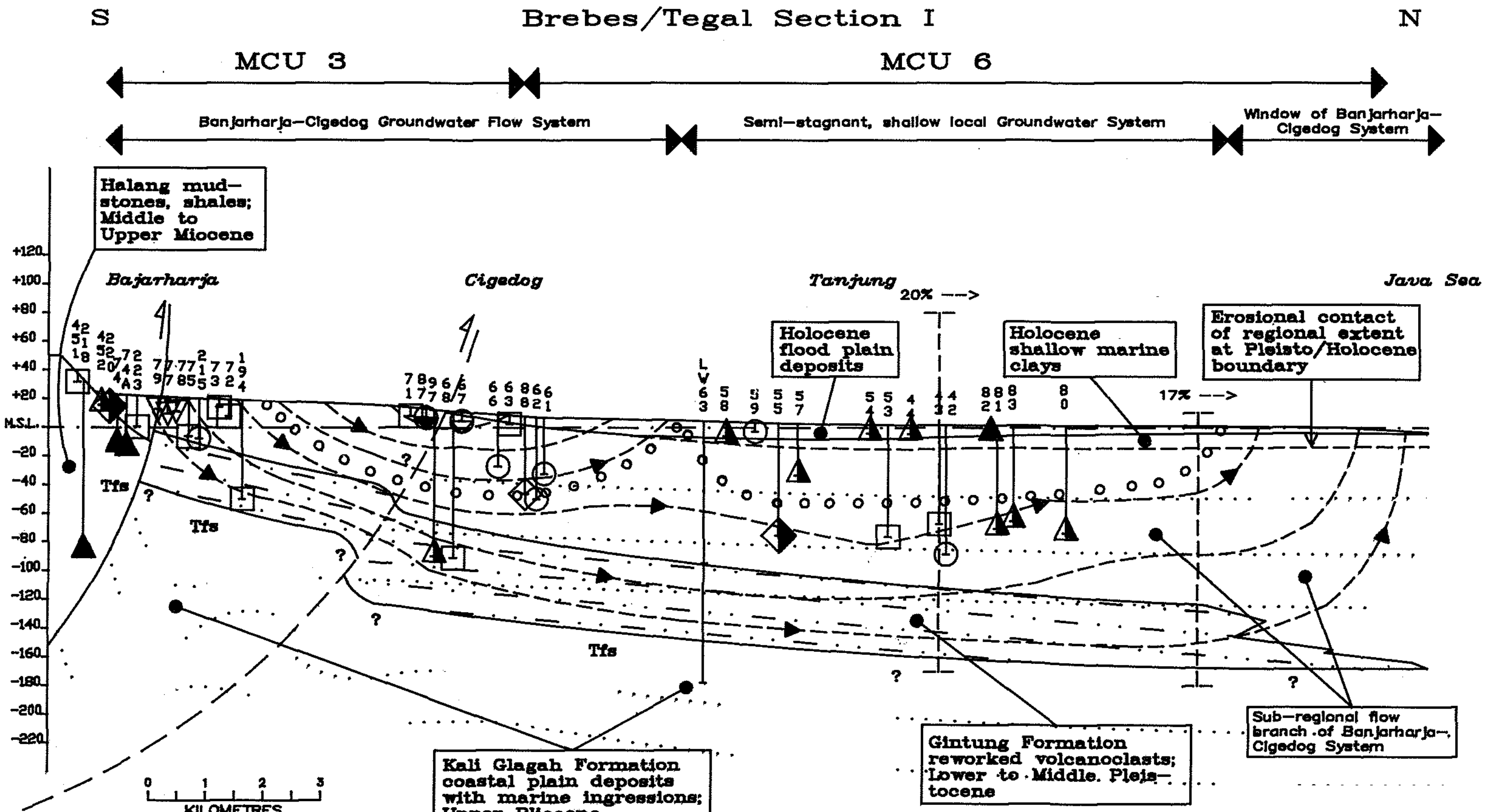


Fig. 7.35 Hydrochemical cross section Brebes/Tegal I (see Fig. 7.5 for general legend).

These Pliocene outcrops are bounded in the south by the Miocene Halang Formation, though structurally separated by an upthrust fault. Highly saline groundwater seepages (EC ranging from 20,000 to 30,000 μmhos/cm) have been found along this fault line. Gischler (1988) reports the failures of five deep tube jettings to depths of 200 m in the vicinity of Banjarharja.

Table 7.15 Characteristic chemical types of groundwater in the marine clays and mudstones of the Upper Miocene Halang Formation.

Id. Nr.	Depth (m)	EC μmhos/cm	pH	Chemical type
74	36.0	5,390	7.6	B3-NaCl +
74A	38.0	4,590	7.6	B3-NaCl
218	120.0	29,400	7.1	S6-NaCl

The Holocene piedmont alluvial plains belonging to morphological unit 3 consist mostly of brown-coloured clayey and silty sands with minor gravel horizons and lenses. However, the deposits may also be developed as stiff flood plain clays which are found for example west of Banjarharja. Dug wells in these stiff clays almost invariably yield highly mineralized groundwaters, often rich in sulphates at several gr/l. These alluvial deposits are built up as numerous coalescing small alluvial fans derived from erosion products of the Tertiary formations, remnants of clastic materials from former higher planation levels (see Fig. 4.8) and volcanic materials from eruptions of the young Slamet. Particularly at the beginning of the Holocene, during the peak in magmatism, most of the hills in the hinterland may have been blanketed by volcanic veneers from ash and tuff showers. At those times of increased magmatism a large supply of volcanic materials is available to build up numerous alluvial fans at distinct topographical slope breaks, by fluvial transport and even mudflows. At present the piedmont plain is being dissected by the larger rivers such as Kali Kabuyutan and Cijangkelok.

The Banjarharja-Cigedog Groundwater Flow System appears to occupy only the section beneath morphological unit 3, thus under the piedmont plain and sloping at about 1.8 m/km. Beyond this piedmont plain groundwater system the deeper groundwater qualities deteriorate and can be classified as brackish NaCl and NaMix types, suggesting that the process of fresh flushing has not yet progressed far enough. The flux of groundwater flow under morphological unit 6, generated by the piedmont plain system, is reduced to only 20% (of a total of 0.25 m^2/day) or about 0.05 m^2/day. Compared with previous cross sections one can conclude that this flux amount is insufficient to flush the deeper sediments. Tube wells 42, 43 and 53 are in fact located further to the west of the section line and fall within the boundary of fresh to brackish deeper groundwater.

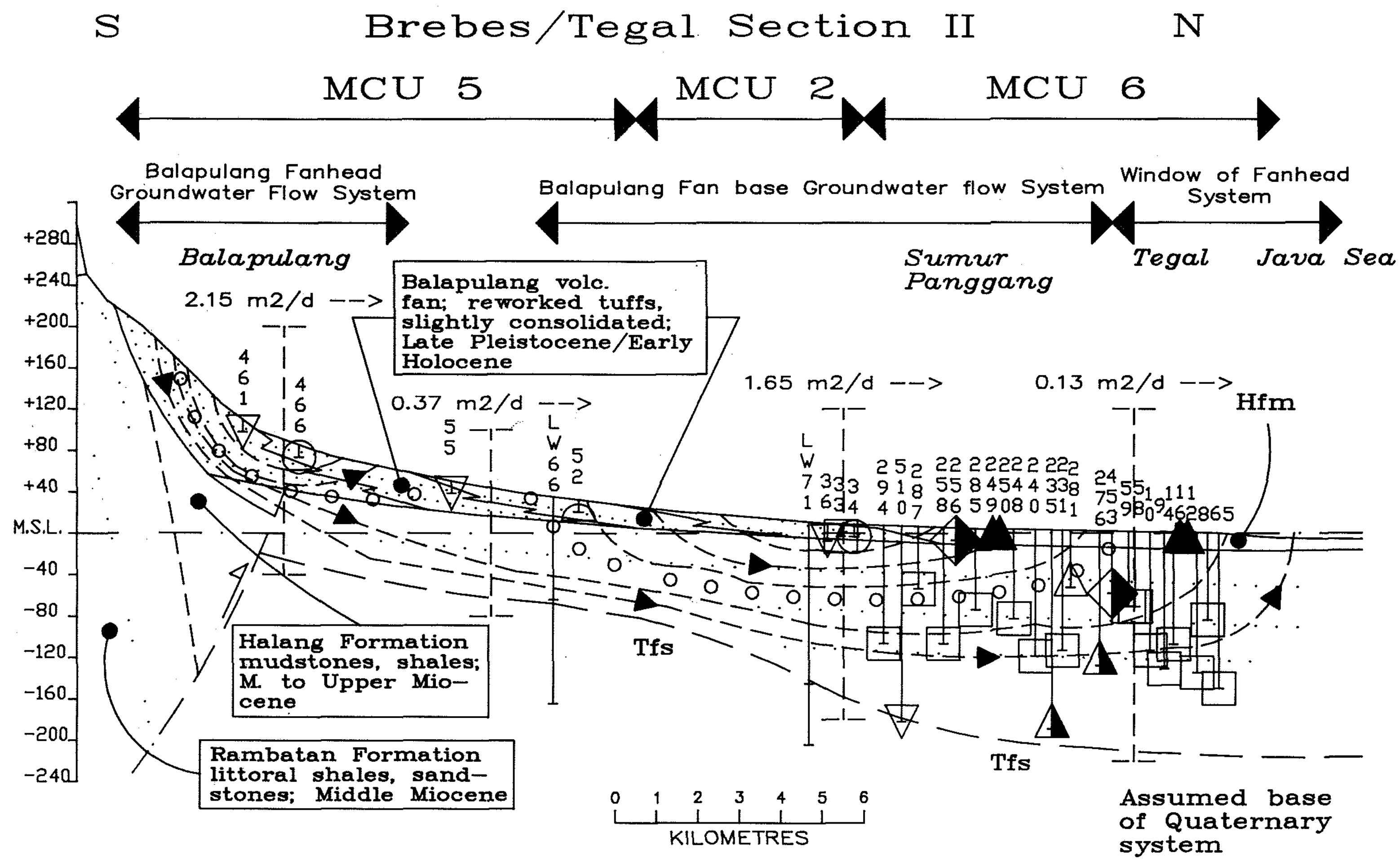


Fig. 7.36 Hydrochemical cross section Brebes/Tegal II (see Fig. 7.5 for general legend).

Cross section Brebes/Tegal II shows the effect of the Balapulang fan on the deeper groundwater flow in the coastal lowlands. Three groups of chemical types are present in this section; fresh $CaHCO_3$ and $MgHCO_3$ types in all parts of the Balapulang fan, the highly saline NaCL types in the Holocene marine clays in morphological unit 6 and the fresh $NaHCO_3$ types in the deeper permeable horizons.

The depth to the bottom of the Quaternary system is conjectural and based on the poor lithological information from exploration bore holes LW66 and LW71 of Public Works. In his study on the possibilities of utilizing groundwater for the piped water supply of the town of Tegal, De Jongh (1923) reports the presence of fossiliferous marls (Pliocene Kaliglagah or Kalibiuk Formation ?) in a 170 m deep borehole in the village Pagongan (3.5 km south of Tegal). He further reports chloride contents of groundwaters from 75-85 m and 97-106 m of 56 and 45 mg/l respectively. Deep wells for the sugar cane factory at Pangkah (approximately at the level of test hole LW66) have been drilled to only 70 m, which might indicate that the underlying Pliocene strata had been reached. The same author notes the rapidly deteriorating deeper groundwater quality to the west of Tegal, which accords with the outline of groundwater qualities shown in Fig. 7.34.

Modelling with FLOWNET reveals the presence of two major groundwater systems: (a) the Balapulang fanhead system and (b) the Balapulang fan base system; a sub-system of the fanhead system. Although most of the groundwater flow of the fanhead system ascends to the surface in the mid section of the fan, 17% or about 0.37 m^2/day still flows to the deeper layers under the town of Tegal. The percentage of flow may seem to be small, but the flux of 0.37 m^2/day is in the same order as the flux which flows for example in cross section Subang III (see Fig. 7.15) and which has led to the same fresh $NaHCO_3$ types. According to FLOWNET the Balapulang fan base system generates a flux of about 1.65 m^2/d.

Although the majority of the groundwaters can be classified chemically as fresh $NaHCO_3$ types, the chloride values are still somewhat higher than expected when compared with other cross sections. The explanation for this phenomenon is perhaps the fact that the coastal/deltaic plain of Tegal is indeed geologically very young. This is indicated by the highly saline dug wells 294, 250 which are contaminated by connate waters from the underlying Holocene shallow marine clays of this regressional coast. It implies that the Holocene coastline, during maximum sea levels at about 4,500 years ago, may have reached the endlobes of the Balapulang fan. Thus the groundwater flow pattern shown in Fig. 7.36 can be expected to have been established only a few thousand years ago and certainly less than 4,500 a. The time span available for fresh water flushing has therefore been very limited. This is in sharp contrast with the West Java situation in which the Late Pleistocene Volcanic Fan Formation, driving the groundwater system, was established in Late Pleistocene-Early Holocene times.

Cross section Brebes/Tegal III is located in front of the gravity glided sectors in the eastern part of kabupaten Tegal. As can be expected from the intricate geological structure in the frontal parts of the sectors, the geology beneath the coastal lowland sediments remains largely conjectural. Extensive well surveys in the area by Hasudungan (1987), Sulistiyanto (1987) and Wijckerheld Bisdom (1988) showed a conspicuous pattern of groups of tube wells, giving the impression that location of the groups is related to the structure and in particular the shorter transverse faults (see Fig. 4.1).

Groups of tube wells with depths between 20 and 50 m are found in the eastern part of this area near the river Kali Rambut and the village Sigentong, but are lacking in the western part near Dukuhrandu and Karangmalang.

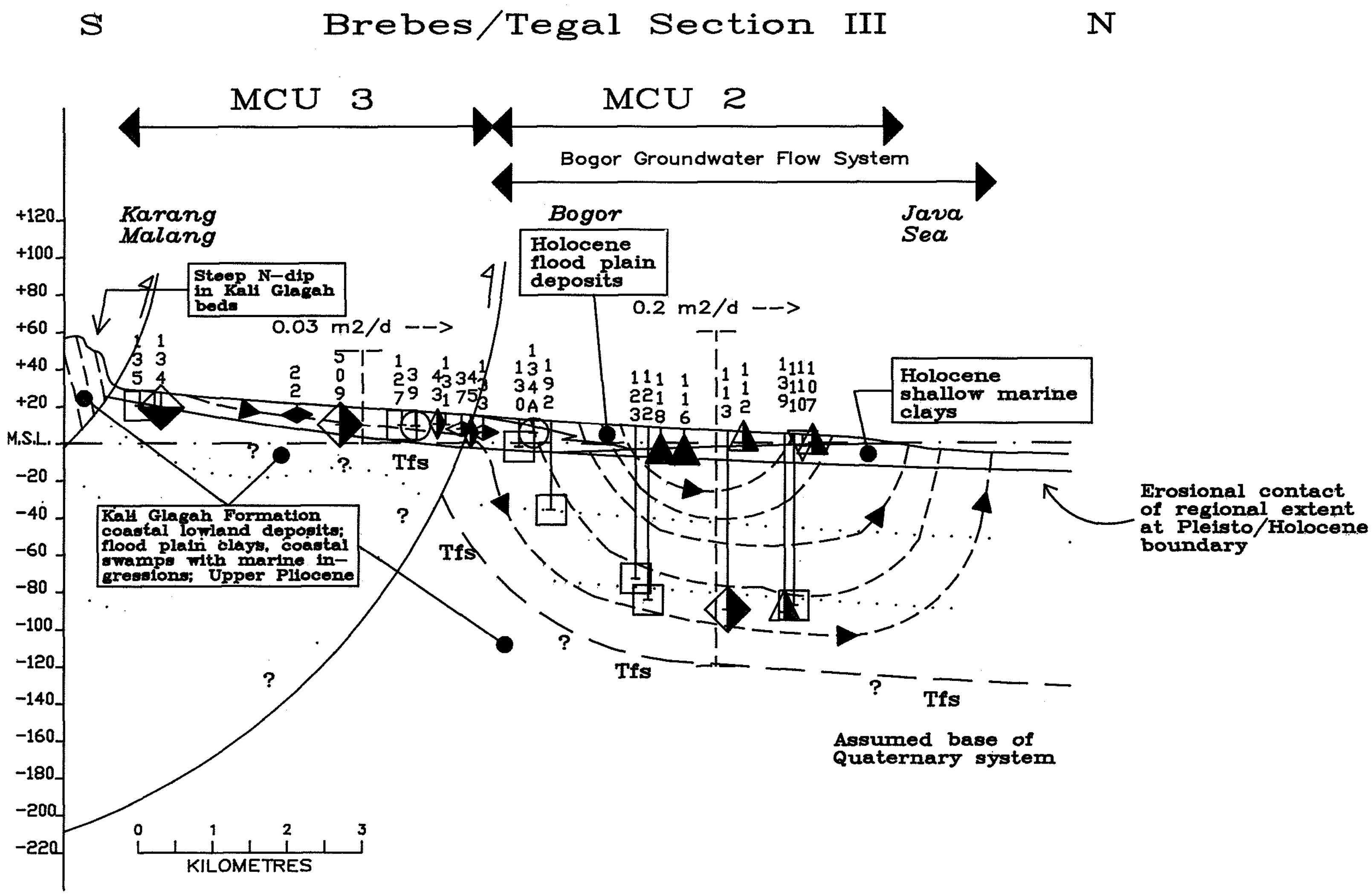


Fig. 7.37 Hydrochemical cross section Brebes/Tegal III (see Fig. 7.5 for general legend).

Even recent attempts to sink deeper tube wells turned out to be failures[5]. The dividing line between the two areas appears to be formed by the SW-NE trending transverse fault which runs slightly to the east of the village Dukuhrandu into the coastal lowlands (see Fig. 4.1). In the cross section this has been interpreted as a shallow depth to the Pliocene basement north of the village of Karangmalang. In that case a second upthrust fault is almost inevitable, as near the village Bogor deep tube wells suddenly appear. The expected positions of these second upthrust faults under the coastal lowlands are indicated on the map of major tectonic structures (see Fig. 7.33).

It must be admitted that the geological structure shown in the cross section is still speculative and based merely on depth configurations of tube wells. However, the absence of any deeper tube wells in the population of open shallow dug wells north of Karangmalang is noteworthy, since the villagers are usually well adapted to the use of pumped tube wells. Moreover, most of the dug wells yield highly mineralized groundwaters which could be an extra stimulus to sink tube wells by simple jetting methods. Based on these facts, the rationale can be constructed of a very shallow depth to the presumably underlying Kaliglagah clays. One may even speculate whether this shallow basement platform might have been connected to the erosional contact of regional extent at the Pleistocene-Holocene boundary, thus forming the Late Pleistocene land surface during the last glacial.

As mentioned earlier, highly mineralized shallow groundwaters occur north of Karangmalang, even up to B5-$NaSO_4$ and b4-$CaSO_4$ types (wells 22, 43, 45 and 133). However, these sulphate types are lacking on the northern side of the proposed second upthrust fault. A cross section through the area constructed by Wijckerheld Bisdom (1988) shows the same feature of sulphate type groundwaters limited to areas with a surmised very shallow Pliocene basement. This conspicuous distribution of the sulphate types may support the geological structure shown in the cross section.

The source of the sulphates should be sought in the Miocene and Pliocene marine clays and shales deposited on a shelf below the wave base and thus under reducing conditions. They can be classed as black carbonaceous shales and mudstones, since the Halang and Pemali Formations in particular constitute the major oil source rocks beneath the coastal lowlands. In terrains underlain by the Pemali- and Halang Formations numerous oil seeps are observable in the field and are also indicated on the various geological maps. This implies that these carbonaceous clays and shales will certainly contain appreciable amounts of pyrite, most likely as tiny disseminated grains of minute crystals (in framboid shape according to Krauskopf, 1985). Sayles & Manheim (1975) investigated interstitial solutions and diagenesis in deeply buried marine sediments and conclude that terrigenous organic-rich sediments deposited rapidly along continental margins exhibit significant evidences of alteration. They mention a complete removal of SO_4^{2-}, strong HCO_3^- enrichment, formation of NH_4^+ and methane synthesis, implying that S becomes fixed in pyrite. Interstitial Cl^- remains relatively constant.

Even the coastal plain deposits of the Kaliglagah Formation contain many intercalations of former coastal swamp deposits with jarosite mottling and cm-large gypsum flakes. However, the main source rock for sulphates must be the Pemali- and Halang Formations, since sulphate groundwater types also occur in Brebes where Pliocene strata are virtually absent

5 Based on investigations by the Geological Survey at Bandung, deep boreholes have been drilled in the village of Karangmalang to overcome the severe problems of village water supply. According to the inhabitants none of the holes drilled to 120 m produced any usable quantities of water and the wells were finally abandoned.

in the hinterlands. After having completed the paths through the erosion-transport-accumulation system which is assumed to take place rapidly, these originally marine clays with their pyrite content are then exposed to oxidation in the flood plains and at a later stage in the shallow groundwater systems, particular near the watertable which may show seasonal fluctuations of metres in flood plain clays.

Krauskopf (1984) gives the following general stoichiometric reaction for the oxidation of pyrite:

$$2FeS_2 + 15/2O_2 + 4H_2O \rightarrow Fe_2O_3 + 4SO_4^{2-} + 8H^+$$

The change in the free Gibbs energy is -528.8 kcal implying that the reaction will proceed to the right. Retarded groundwater flow such as can be expected north of Karangmalang will in all likelihood not be able to flush the newly formed sulphate-ions resulting from pyrite oxidation, especially in the low-permeable flood plain clays. The sulphate types of shallow groundwater are discussed in further detail below.

In terms of groundwater systems the Bogor Groundwater Flow System can be developed only to the north of the surmised second upthrust fault and thus north of the basement platform. The terrain slope of morphological unit 2 of about 2.6 m/km is capable of generating a major system with a flux of 0.2 m^2/day. Chemical types of the deeper groundwaters (fresh to brackish $NaHCO_3$ and NaMix) support this assumed groundwater system.

7.8.6 *Highly mineralized shallow groundwaters in southern parts of the coastal lowlands*

As was touched on above, strongly mineralized shallow groundwaters are frequently present in the piedmont plain areas. The pattern of occurrence is very erratic; two dug wells at a distance of several metres may yield groundwaters with totally different electrical conductivities. Dug wells which penetrate only clay layers in the piedmont plain are usually strongly mineralized and show a behaviour similar to that described for the dug wells in Cimanuk delta. This behaviour is characterized by large seasonal fluctuations with low water levels at the end of the dry season and maximum salinities. After the first rain storms at the beginning of the wet season the water level reacts rapidly and rises almost to groundlevel with much lower salinities. For example in Brebes, near Karangbale, two dug wells have been found with a separation of only few metres in which one well showed this typical behaviour and the other, which had been dug slightly deeper to a gravelly layer, displayed small seasonal fluctuations and more or less constant water qualities and above all a much lower salinity.

As was described above, the piedmont alluvial deposits comprise three major components:

1) erosion products from the Tertiary fine-grained argillaceous formations;
2) remnants of clastic materials from former higher planation levels;
3) volcanic materials from eruptions of a young Slamet volcano.

The Tertiary clay and shale formations in the hinterland with thin soil covers are particularly prone to infrequent but catastrophic slope failures during prolonged heavy rains. In addition, riverbank undercutting during high flows is an effective erosional tool in creating mass movements. Chorley et al. (1984) consider these monsoonal tropical areas to be 'first-order morphogenetic regions', implying highly infrequent and episodic erosional activities.

Table 7.16 Characteristic chemical types of shallow groundwater (depth less than 15 m) in the piedmont plain areas of kabupatens Brebes and Tegal.

Id. Nr.	Depth (m)	EC µmhos/cm	pH	Chemical type
9	9.0	882	7.4	F2-CaHCO3+
17	7.1	1,309	8.0	F3-CaHCO3+
18	8.2	3,160	7.6	f3-CaMix +
22	5.8	6,300	8.0	B5-NaSO4 +
22	9.8	7,010	7.5	B4-NaCl ·
33	4.2	2,660	7.6	f4-MgMix +
37	8.4	6,230	7.6	b4-NaSO4 +
37	8.4	6,450	8.0	b5-NaSO4 +
39	8.0	1,400	7.7	F3-MgHCO3+
39	8.0	1,569	8.2	F3-CaHCO3+
43	5.0	3,510	8.0	b4-CaSO4 +
45	10.4	3,800	8.0	b4-CaSO4 +
45	10.3	8,110	7.7	b4-NaSO4 +
69	5.4	2,890	7.2	B5-NaCl 0
87	5.0	2,930	7.9	b4-CaMix +
115	9.0	707	7.3	F3-CaHCO3+
119	10.2	1,890	7.9	F2-NaMix +
125	7.9	1,900	7.3	f3-MgMix +
127	7.2	2,250	8.2	f3-NaHCO3+
133	8.6	6,450	8.1	b5-NaSO4 +
134	7.3	1,230	7.4	F3-MgHCO3+
134	7.4	1,040	8.0	F3-CaHCO3+
220	9.0	2,830	8.1	b2-NaMix +

The enormous masses of clayey materials detached by mass movements will slump and slide towards the drainage systems and will probably be transmitted rapidly through the ETA systems and accumulate as mud layers on the alluvial fans in the piedmont plains. It stands to reason that these erosion products of the Tertiary formations are responsible for the strong deterioration of the groundwater qualities, since neither the original saline pore waters nor the finely disseminated pyrite are flushed during their rapid deposition. Terzaghi & Peck (1967) describe the structure of clay particles in sediments formed exclusively from clay minerals. In their view the principal fabric of particles surrounded by repulsive and attractive forces is that of an edge-to-face arrangement of terrace-shaped or plate-shaped clay particles which combine into flocs. Natural sediments will likely consist of aggregations of these flocs with the consequence of having voids filled with pore water. Consolidation and swelling involves transfers of water with dissolved solids in and out of these voids. The authors give an example of marine clays with considerable concentrations of salts in the voids occupied by connate waters.

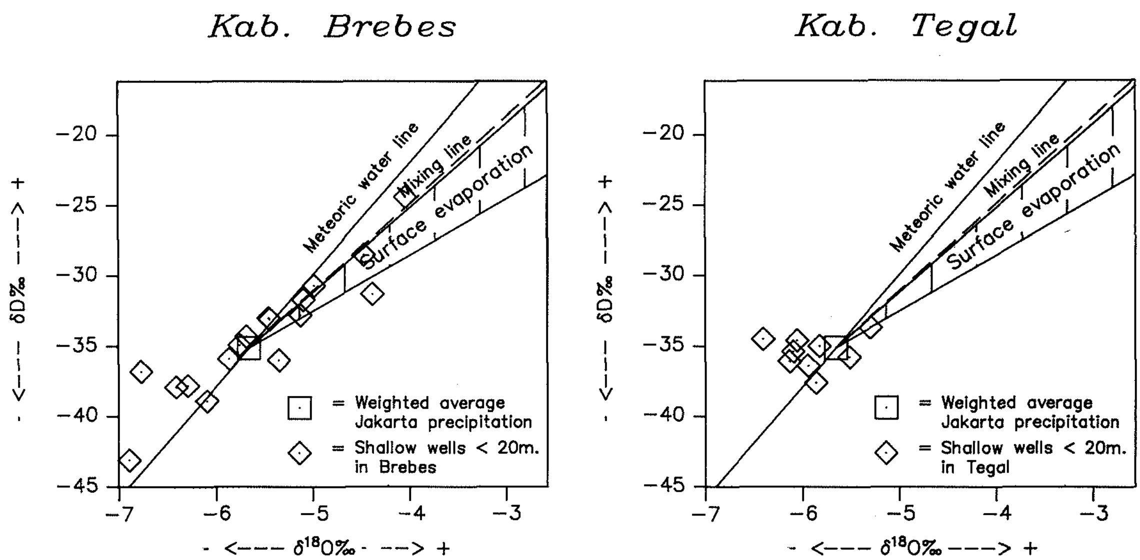


Fig. 7.38 Stable isotope composition of δ^2H and $\delta^{18}O$ in samples of shallow groundwater for the piedmont plain deposits in Brebes and Tegal.

It should again be emphasized that small springs, shallow wells, seeps and base flows in the Tertiary clay and shale formations are generally strongly mineralized with EC values which far exceed 1,000 μmhos/cm. The hydrochemical types of a number of shallow wells with a depth of less than 15 m in kabupatens Brebes and Tegal are listed in Table 7.16. The complete chemical analyses are given in Appendix II. It follows from the table that the shallow groundwaters are heterogeneous in chemical type. Waters are found which vary from pure fresh $CaHCO_3$ and $MgHCO_3$ types up to the highly mineralized $NaSO_4$, $CaSO_4$ and NaCl types. $NaHCO_3$ types with relatively high pH values, characteristic of ion-exchange processes, are also present.

To continue the discussions on shallow groundwaters in the Cimanuk delta (see section 7.5.4), oxygen and deuterium isotope fractionations have also been determined by Wijckerheld Bisdom (1988) and Gischler (1988) for the shallow groundwaters in Brebes and Tegal. The main objective of the isotope analysis is to test the hypothesis of direct evaporation of soil water as the sole salinization mechanism. The results are again shown in standard form (Mook, 1984) by Fig. 7.38. The diagrams reveal the same pattern found for Cimanuk delta wells; most samples approximate the weighted average values for Jakarta precipitation and the two samples from wells in the Miocene Halang Formation at Brebes plot close to the mixing line. One must therefore arrive at the same conclusion that these diagrams do not positively support the evaporation hypothesis.

Contrary to the flat lower parts of flood plains with stagnant groundwater, the piedmont plains in the kabupatens Tegal and Brebes are characterized by appreciable terrain slopes and furthermore normal dendritic drainage systems are present incised into these plains. It is logical to assume normal circulation by local groundwater flow systems and flushing of salt accumulations in the soil by evapotranspiration.

This then leaves as the principle salinization mechanism the dissolution of interstitial pore waters with flushing of adsorbed ions and oxidation of pyrite from flood plain clays and silts derived from the Tertiary hinterlands. The amount of soluble salts entered into the systems by the rapid deposition of erosion products of marine argillaceous rocks from the hinterland obviously requires a considerable span of time to be dissolved and flushed out of the system by natural groundwater flow.

7.8.7 *Conclusions on groundwater hydrochemistry in kabupatens Brebes and Tegal*

The following conclusions can be drawn with respect to groundwater investigations in kabupatens Brebes and Tegal:

1) the fundamental difference between the coastal lowlands of Brebes and Tegal and those in West Java, west of the river Cimanuk, is the absence in the former of the Late Pleistocene Volcanic Fan Formation. The influence of the Fan Formation as expressed in patterns of lowland sedimentation and regional groundwater flow systems is thus lacking in Brebes and Tegal. The Late Pleistocene Volcanic Fan Formation is at present being dissected and attacked by fluvial erosion, whereas the piedmont plains in Brebes and Tegal still form accumulation areas;
2) the Balapulang volcanic fan is of paramount importance in generating a sub-regional groundwater flow system which extends far beyond its fan base. The fresh to slightly

brackish deeper groundwaters near the town of Tegal are produced by fresh flushing processes, driven by the Balapulang flow system;

3) the division of the coastal lowlands into domains with similar groundwater qualities runs concentrically around the lower Balapulang fan segments;
4) the fact that deeper groundwaters near the town of Tegal are not yet fully flushed by the Balapulang fan groundwater flow system may be attributed to the young age of the fan and the position of the Holocene coastline which was situated further south;
5) the geological structure of sectors which have glided outwards under gravity forces in the eastern part of kabupaten Tegal is considered from hydrogeological evidence to continue under the present-day coastal lowlands and controls the position of the groundwater flow systems;
6) the strongly mineralized shallow groundwaters in the piedmont plain areas of Brebes and Tegal are caused by dissolution of interstitial pore waters and adsorbed ions on clays and silts in flood plain deposits and mudflows. The clays and silts are derived from the Tertiary marine clays, shales and marls in the hinterlands. The high sulphate contents are the result of oxidation of finely disseminated pyrite in these carbonaceous Tertiary clays and shales.

7.9 Remaining aspects of groundwaters in the northern coastal lowlands

7.9.1 Artesian flow

Deeper tube wells yielding groundwater under artesian pressure are commonplace in the coastal lowlands. Many large diameter deep wells constructed in the pre-war period under the colonial government have been self-flowing for decades. It is in fact amazing that not only could artesian wells be drilled in the coastal lowland proper, but that pre-war artesian wells have also been implemented on a few small islands in the bay of Jakarta.

During the drilling process of tube wells or large diameter wells by jetting methods the erratically distributed water-transmitting layers are easily recognized when the jetting pipe suddenly meets artesian pressures. Unfortunately not all the deeper wells have remained self-flowing and in most cases a pump has had to be installed eventually.

Table 5.2 showed that from a total of 3,357 surveyed wells in the six kabupatens 430 wells were entered in the data base as artesian tube wells at the time of surveying. Fig. 5.5 gives the depth frequency histogram for the artesian tube wells, indicating that self-flowing tube wells are generally at depths of 50 m or more, thus starting in depth cluster 1. The very shallow artesian tube wells are found locally in kabupaten Indramayu on the Late Pleistocene Volcanic Fan Formation near Cikedung and Lelea and can be considered as real artesian wells in the classical sense

A number of major artesian tube well characteristics can be listed which may shed some light on their hydrogeological nature:

1) discharges of self-flowing tube wells are without exception reported by the local inhabitants to be declining constantly. It is said that small diameter tube wells will usually last less than five years before pumping becomes necessary. However, it can be expected that the poor technical construction of tube wells with no proper screen will

be a further crucial factor. Deep wells drilled in pre-war days which have yielded groundwater for decades under artesian pressures are also found to have been subjected to strongly decreasing yields, even in areas which are practically devoid of other deep wells. Regular visits by the present author to self-flowing tube wells in the course years have confirmed this effect of constantly lowering hydraulic heads;

2) it is hard to discern a coherent pattern among areas with overpressured deep tube wells with respect to their location in the lowlands, depth of permeable horizons with artesian pressures and elevation of the piezometric head. Thus in the same way as the forecasting of depth to permeable horizons, areas which will most likely be favourable for self-flowing tube wells can be identified at a sub-regional to regional scale by systematic well surveys. However, on a local scale artesian tube wells differ widely in total depth, duration of artesian flow and piezometric head. The piezometric heads of tube wells in particular, with similar total depth and within a radius of say one hundred metres, can differ widely from a few centimetres above ground level to as much as two metres[6]. A situation often encountered was that in which a tube well ceased to be self-flowing whereas a nearby well, a few metres deeper or even shallower, had not yet reached that stage. In general static heads of artesian tube wells are found to vary randomly. Newly drilled tube wells will exhibit high initial overpressured conditions which reduce rapidly in the course of a few days to normal pressures;

3) self-flowing tube wells may occur everywhere in the coastal lowlands and are not necessarily limited to a near-coastal belt. Artesian tube wells are present even in the southern periphery of the lowlands in the infiltration areas for the major groundwater systems.

Deep wells drilled in the pre-war period after the turn of the century are generally well-documented with respect to initial static heads. Much information is available in the annals of the former Mining Department in Bandung, the 'Jaarboek van het Mijnwezen'[7]. A few deep wells from the pre-war period are listed in Table 7.17 as an illustration of the original static heads at various depth levels. The wells Anjatan and Kadokangabus, for example, were characterized after completion in 1912 by high static heads of more than 10 m, although the deepest layer in the Anjatan well recorded a static head of only 6.9 m. Even the tapped layer at a depth of 25 m in the Kadokangabus well experienced a water level rise of almost 6 m above ground level. A sharp increase of static head is found at 60 m. The horizons at 25 and 40 m are situated within the Late Pleistocene Volcanic Fan Formation and may represent artesian systems in the classical sense, which is also suggested by the more or less equal heads. Kadokangabus is located in the southern part of kabupaten Indramayu in areas with appreciable terrain slopes (see Fig. 7.17). The deeper layers with heads of more than 12 m are found in the clayey sediments underlying the Fan Formation. During the field campaign in December 1980, the Anjatan well (well Idnr. 34 in Fig. 7.19) was reportedly negative since the previous year and the other well (position in Fig. 7.20 near well Idnr. 74) was said to have been negative for years and was finally abandoned. It should be

---

6 Artesian tube wells such as found in the rural areas consist only of a riser pipe with a double socket bend and horizontal outflow pipe, which is very convenient for a plastic hose connection to give static head measurements.

7 The complete set of 'Jaarboek van het Mijnwezen' dating back to the end of the last century is available at the Nederlands-Indisch Archief of the Koninklijk Instituut voor de Tropen, Amsterdam.

remembered that both wells are situated in areas with low densities of recent tube wells, since the area is underlain by the Late Pleistocene Volcanic Fan Formation and thus allowing the construction of open dug wells with good quality groundwaters. This is particularly the case for the Kadokangabus well. Contrasting initial static heads are further reported for the wells Ambulu Wetan and Losari Kidul in Cisanggarung delta at the Cirebon and Brebes boundary. The Losari Kidul well was still self-flowing in September 1983, albeit at a very small discharge of less than 180 l/hr. If a static head of 6.9 m for the layer at 102 m depth is considered correct for the Ambulu Wetan well, then a decrease in static head occurs in the deeper layers; layers at 133 and 143 m depth recorded static heads of only 3.4 and 3.6 m respectively. The deepest layers at 133 and 143 m in the Ambulu Wetan well and at 146 m in the Losari Kidul well may already be situated within the Middle Pleistocene Gintung Formation built up by reworked volcanics and fluvial deposits, thus mainly lithic materials.

Table 7.17 Initial static heads above ground level for a number of pre-war large diameter deep wells, as recorded in the 'Jaarboek van het Mijnwezen'.

Year	Kabupaten	Well	Average layer depth (m)	Static head above G.L. (m)
1912	Indramayu	Anjatan	100	9.5
			107	10.0
			122	16.2
			153	6.9
1912	Indramayu	Kadokanga-gabus	25	5.9
			40	6.2
			60	12.4
			65	12.8
			75	13.1
1916	Cirebon	Ambulu Wetan	102	6.9
			133	3.4
			143	3.6
1916	Cirebon	Losari Kidul	38	2.3
			58	3.0
			65	3.4
			77	4.6
			146	4.0
1916	Brebes	Brebes I	50	1.5
			114	6.0
			130	6.3
			158	6.0
1922	Indramayu	Kroya	52	4.0
			60	8.4
			100	11.0
1923	Indramayu	Gantar	92	15.5
1927	Tegal	Duku Badur	25	1.5
			31	1.7
			36	1.6
			106	1.8
			127	2.0
			140	3.5
1929	Kendal	Weleri	42	-2.1
			70	-1.5
			130	-1.5
			190	-1.7

The Brebes well, also situated in a young Holocene delta exhibited similar static head values, although a deep continuation of the volcanic Gintung Formation as far as the town of Brebes is not expected. The wells Kroya and Gantar are situated in the southern parts of kabupaten Indramayu where the Late Pleistocene Volcanic Fan Formation is exposed (Idnr. 74 in Fig. 7.20 and Idnr 8 in Fig. 7.19, respectively). Kroya is reported by the local inhabitants to have been negative since 1978. This well is also very peculiar in its static head versus depth relation; two layers separated by only 6 m in depth (layer 1, 50-53 m and layer 2 59-61 m) are reported to have a static head difference of 4.4 m. This Kroya well resembles much the Kadokangabus well in that a similar sharp head increase is recorded at levels deeper than 60 m. Again a plausible explanation is that the level at 52 m is still found within the Late Pleistocene Volcanic Fan Formation and therefore may represent a classical artesian system with original heads similar to Kadokangabus.

In 1921 another deep well (Tjipinang) in the Jakarta area exhibited positive static heads of about 1 to 2 m down to layer depths of 206 m, but the two deepest layers at 230 and 245 m were found to have negative heads of -2.25 m.

The Gantar well still produced a discharge of 0.05 l/s as per September 1980. However, according to the 'Jaarboek van het Mijnwezen' the well, which has a screen in only one layer from 90 to 93 m, yielded a flow of 1.25 l/s just after completion in 1923. Based on these figures a decrease in yield from 1.25 to 0.05 l/s took place in a time span of 57 years. Assuming a logarithmic depletion curve, an exponential function of the following simple form can be fitted:

$$q = a \; e^{-bT} \qquad (7.1)$$

where,

q = discharge in l/s at time T
T = elapsed time in seconds after well completion
a = constant
b = constant

The constants a and b are easily determined as a = 1.25 and b = 1.8E-9. The next step is to calculate the total amount of water produced by the well in 57 years by determining the integral of 7.1 between the time boundaries T = 0 to T = 1.8E+9 seconds. With boundary conditions Q = 0 at time T = 0 this yields:

$$Q = (-a/b) \; e^{-bT} + (a/b) \qquad (7.2)$$

Inserting the relevant parameters in 7.2 results in Q = 6.67E+8 litres as a total amount of water produced during the well lifetime. One may further assume that water is released from storage from a hypothetical layer 3 m thick with an effective porosity of say 5%. The radius of this hypothetical cylinder thus amounts to 1,190 m. This figure serves as a rough indication of the radius of influence, from which it can be concluded that the amount of groundwater stored in such a hypothetical thin aquifer is sufficient to sustain a self-flowing large diameter well for decades under unsteady-state flow conditions. It also implies that groundwater released from storage by compaction of aquifer horizons without receiving any recharge is still capable of yielding groundwater to these pre-war deep wells for decades.

The deep well Duku Badur situated in the eastern part of kabupaten Tegal, along the coast, appeared to be still positive in July 1986 but the discharge had decreased to about 0.2 l/s and finally stopped flowing in 1987. The original chloride content of the water was 156 mg/l in 1927 and a sample taken in July 1986 contained about 400 mg/l. An interesting pre-war deep well which is different from the ones so far discussed, is the well in Weleri, a small town in the coastal lowlands about 40 km west of Semarang (see Fig. 4.5f). This well withdrew groundwater from the fairly permeable Upper Damar beds, consisting of fairly coarse volcanoclasts, and presumably also from the deeper Middle Damar beds. None of the tapped layers showed a positive piezometric head in 1929 which fits into this hydrogeological framework of competent arenaceous and rudaceous rocks without overpressured conditions.

Table 7.18 Initial static heads above ground level and original chloride contents of wells drilled on small islands in the Bay of Jakarta, as recorded in the 'Jaarboek van het Mijnwezen'.

Year	Island	Well	Average layer depth (m)	Static head above G.L. (m)	Initial Cl content (mg/l)
1912	Kuiper (Pulau Cipir)		172 190	 3.9	713 934
1922	Onrust (Pulau Kapal)	Onrust V	150 234	1.2 4.0	416 1512
1922	Edam (Pulau Damar B.		103	Pump installed	

As touched upon earlier, deep wells were drilled not only at the coast but also on a few small coral reef islands in the bay of Jakarta. Table 7.18 outlines the main characteristics of these pre-war deep wells. The last mentioned well in the table, previously Edam but now Pulau Damar Besar is situated 17.5 km north of Jakarta, whereas the other two are located 2.5 km offshore from kabupaten Tanggerang, west of Jakarta. It is amazing that the artesian conditions appear to continue beneath the present Java Sea and furthermore, although the groundwaters are classified as brackish they do not have salinities typical of the Java Sea.

Table 7.17 thus clearly indicates a general tendency to increasing original static heads with depth in particular in incompetent clayey sediments, nevertheless inversions in head have been reported (Ambulu Wetan, Losari Kidul, Brebes I, Duku Badur and Weleri) and large jumps in static head may also have existed over short depth intervals. Gradually increasing heads versus depth and inversions over short depth intervals are not expected in classical artesian systems not yet disturbed by groundwater abstractions.

From a geological viewpoint the Quaternary sedimentary basins north of the major hinge zone on Java can be classified as a marginal basin association filled with fine-grained clastic wedges. They comprise fluvial, deltaic and shallow epicontinental marine environments. Under humid tropical climatic conditions the sediment input is predominantly fine-grained, transported in suspension by the major streams and derived from Tertiary marine calcareous mudstones and shales, Tertiary and Pleistocene fossil soils and from various reworked or airborne volcanic sources. Under tropical wet-dry conditions the weathering processes shift to mechanical disintegration of rocks, but the source materials remain the same with the exception that during strong magmatic outbursts much coarse-grained volcanoclasts may also become available. To return to the problem of artesian pressures in the coastal lowland aquifer zones, one may deliberate on the dominant type of clay mineral in the argillaceous sediments of the Quaternary basins. Out of the three major groups of clay minerals, the illites, kandites and smectites, the latter is in all likelihood the dominating group. Although much confusion exists on the occurrence and origin of clay minerals most workers agree on the general paragenesis for smectites: alteration of basic rocks, calcic-mafic volcanic materials, alkaline conditions and availability of Ca and Mg (Deer et al., 1972, Pettijohn, 1975). Since montmorillonite is the principal variety in the smectite group, one may expect this three-layer clay mineral with marked swelling properties and very large ion-exchange capacities to be dominant in sediments derived from volcanic materials. The major type of clay mineral in the shallow marine sediments is still obscure, since Krauskopf (1985) states that illite is the most common in marine sediments. However, Krauskopf further states that in mixtures of two or more clay minerals the overall properties may be greatly influenced by the minor constituent, particularly in the case of montmorillonite in which a small percentage can radically change the plasticity of the clay mixture.

Hinch (1980) discusses at length the nature of compaction in shales leading to hydrocarbon expulsion. Although the purport of his article is mainly concerned with hydrocarbon expulsion at depths of more than 1 km, general agreement exists on the presence of a shallow zone above the so-called Compaction Stage 1 (from about 700 to 3,500 m). In this shallow zone which extends to the sediment surface, mechanical rearrangement takes place with rapid decreases in porosities of the newly deposited sediments. Initial porosities may reach values of 80 to 90% in montmorillonite clays, reducing to about 50% at depths of 250 m. In the model proposed by Krauskopf (1967), mechanical rearrangement involves the structural breakdown of flocs formed by the plate- or terrace-shaped clay particles. Destruction of the flocs entails expelling pore water from the voids which are formed by floc aggregations. Part of the energy in mechanical rearrangement is accounted for by elastic deformation of the particles (Krauskopf, 1967). Gilliot (1968) in a treatise on the fabric of clay soils based on the findings of a number of scholars, concludes that clay particles deposited in fresh water tend to have a more or less parallel close-packed type of orientation. Clay sedimentation in quiet marine environments on the contrary is characterized by an open flocculated arrangement with contacts between edges and faces, also termed the 'honeycomb structure'.

It can be concluded from the above discussions that the deep artesian wells in the coastal lowlands and the small islands in Jakarta Bay are driven by compaction of the clayey Quaternary sediments. The clayey sediments are subjected to loading from the overburden leading to a reduction of the void ratio. As the permeability is very small in these montmorillonitic marine shelf muds and flood plain clays, it follows that expulsion of the pore waters will also be a very slow process and therefore the overburden load is largely carried by the water. Compaction is the transference of load from the interstitial water to the mineral particles. Sinking a tube well in these sediments with a hydrostatic excess pressure is a way of bleeding this overpressured reservoir and speeding up the compaction process. The load of the overburden becomes then transferred at increased rates to the skeleton of mineral particles, which in case of clay minerals with a honeycomb fabric allows for considerable reduction in void ratio and thus further decreases permeability and porosity.

Engelen (in Engelen & Jones, 1986) distinguishes three major vertically imposed zones of groundwater flow of which the middle zone is a shrinking connate system. Sinking a deep well in such a system is simply creating a window to the surface which locally induces compaction driven flow.

With respect to the Quaternary basins the following arguments can be advanced to favour compaction driven flow:

1) the hydrostratigraphic build-up in the basins contradicts with the classical concept of rigid thick aquifers separated by thinner semi-confining layers found in true artesian basins. On the contrary, the entire sediment pile has a fine-grained lithology and at certain consistent depth levels only, at least three in this study, horizons occur with a significant probability of finding a permeable layer. However, the thicknesses of these locally ill-defined horizons are small compared to the fine-grained members of the total sediment pile. It follows that a well-defined omnipresent semi-confining layer as found in a classical gravity driven artesian system is missing. The high static heads measured for example in the pre-war deep wells in Indramayu at remote distances from the infiltration areas, would require unrealistically high vertical hydraulic resistivities in the overlying aquitard;
2) the total maximum flux of gravity driven natural flow for major systems in southern parts of the lowlands, as calculated in a rigid vertical model by FLOWNET, amounts to only 0.2 to 0.4 m^2/day. Theoretically this may presumably have been enough to sustain the few deep wells in pre-war times, but not for the present population of tube wells. When sustained by natural groundwater flow an approach to a quasi-steady state situation is then to be expected, which has not been found;
3) the expected dominance of the three-layer type montmorillonite clays with extreme high porosities are not likely to contribute to the classical type of rigid artesian systems;
4) the local effect of groundwater withdrawals and the apparently random distribution in elevation of the static heads. Moreover, inversions of static head may occur in deeper layers;
5) the artesian wells on the small islands in Jakarta Bay;
6) slowly increasing salinities in well waters of the old colonial deep wells can be explained by compression of marine clay layers enveloping the more permeable sandy layers from which groundwater is withdrawn by the wells. The continued production of groundwater under unsteady state conditions lowers the hydrostatic pressure and as a consequence increases the pressure on the clay layers, thus squeezing the more saline connate pore waters into the sandy layers.

However, this type of assumed compaction driven flow is still very peculiar and requires other mechanisms to be active on a very local scale. One may wonder whether the high static heads reported in the 'Jaarboek van het Mijnwezen' are correct or do in fact reflect the actual situation, since they apply to situations during or only shortly after the drilling operations. The following summarizes the most peculiar features:

1) the artesian pressure of the deep wells keeps on decreasing and even the wells which have become negative and have been abandoned do not show any recovery of the static head, irrespective of the riser pipe and screen construction being still undamaged and unclogged. If the compaction has reached a final limit within a certain radius of the well, one may expect water to flow into that compacted sector from exterior parts of the sediment pile which still allow further compaction. However, prolonged self-flowing conditions will probably lead to strongly compacted clays and silts encasing the more permeable horizons in the vicinity of well screen or tube well ends from which groundwater is withdrawn. The strong compaction further lowers the permeability and porosity and may eventually cause an effect of 'sealing' the well;
2) apparently only during the pre-war period have such high static heads been encountered in deep wells. The present author has not yet experienced such phenomena from first hand. Even visits to drilling sites in which large diameter wells were drilled using a casing following the jetting pipe have never revealed such extremely high static heads. Tube wells tapping shallow layers at depths of 25 m with static heads of several metres above ground surface (such as reported for the Anjatan well; see Table 7.17) have not been found during the current field surveys. None of the deep test wells drilled by the Indonesian Department of Public Works (PU/P2AT) in the framework of a regional groundwater development programme in the kabupatens Brebes and Tegal, in areas with very low tube well densities, exhibited positive static heads. Nevertheless, one still might attribute these high original static heads as recorded for pre-war wells to drilling techniques. Careful drilling with a casing following the bit may perhaps reveal these high initial overpressures in the thin sandy layers, whereas during modern rotary drilling such high pressures may remain largely unnoticed. Once more it should be stressed that during the field campaigns the measured discharges of self-flowing tube- and large diameter wells were very small; a sample of 266 wells showed an average value of merely 0.21 l/s[8];
3) a special feature is the amazingly small radius of influence of neighbouring wells; also noted by IWACO/WASECO (1987b) in a report concerning a hydrogeological reconnaissance study of kabupaten Bekasi. IWACO mentions large groundwater withdrawals in the area of the town of Bekasi (about 5,000 m^3/d), while only 3 km to the NE self-flowing wells are still evident. This phenomenon has also been observed by the present author; self-flowing tube wells have often been encountered in the field in the vicinity of old negative colonial wells apparently tapping water from the same layers. The effect of 'sealing' the more permeable sandy layers by the strong compacted enveloping clays and silts is a possible explanation for this phenomenon. However, in case of pre-war wells one may obviously attribute this effect also to col-

8 The maximum yield was 1.5 l/s and the smallest 0.01 l/s. For this population of 266 wells the standard deviation is 0.25 l/s.

lapse or screen clogging of the old wells or short-circuiting between the permeable layers tapped by these old wells.

One might expect that drastic changes take place in the skeleton of platy clay particles. An abrupt change in the structure of the floc aggregation, giving the impression of a structural collapse, will reduce the voids and increments the load on the pore waters which is manifested by high initial hydrostatic excess pressures. Terzaghi & Peck (1967) stress the phenomenon that the positions of clay particles found in many sediments are 'not necessarily associated with equilibrium of the various attractive and repulsive forces'. Clay particles may therefore rotate to attain more stable configurations which may lead to contraction of the original volume. Terzaghi & Peck describe another phenomenon, not yet fully understood but found both in the field and during laboratory experiments, namely the strong increase in sensitivity of marine clays when the concentration of sodium ions in pore waters is reduced by leaching. This effect can presumably also be achieved in marine clayey deposits, once containing saline connate water and flushed by fresh groundwater flow systems. This situation is likely to occur in the well flushed deeper layers in some southern areas of the coastal lowlands, where the chemical type of groundwater has passed through the desalinization series from NaCl to $CaHCO_3/MgHCO_3$ in final stages.

Contemplating variations, in particular the inversions, in original static head such as listed in Table 7.17, the following mechanisms can be mentioned which are thought to cause these differences in static head:

1) differences in permeability and porosity in clays and silts. Higher permeabilities allow a better transmission of overpressured interstitial water, resulting in lower hydrostatic excess pressures as compared to less pervious layers in the sediment pile;
2) rearrangement of clay mineral flocs from an original honeycomb structure to a more parallel arranged structure by loading or removal of certain adsorbed ions;
3) lithology of the sediments ranging from low permeability marine clays and shelf muds with phenomena of overpressured pore waters to reworked lithic volcanics and sandy to gravelly fluvial deposits forming rigid grain skeletons with groundwater under normal hydrostatic pressures;
4) the expected effect of sudden loadings on top of the clayey sediment pile with overpressured pore waters by lahar flows and other volcanic fans spreading rapidly from the hinterlands into the lowlands, which may increase the excess pressures;
5) it was learned from local authorities in Brebes that thunderstorms with strong winds, occurring once in a few years caused level variations up to 2 m, both negative and positive, in deep observation wells equipped with recorders

Based on the discussions above one may expect three major phases in water pressure decline after sinking deep wells in the clayey sediment pile of the lowlands:

Phase 1: after drilling down to sandy depth zones high initial overpressures will be met, which are transmitted through the sandy horizons. Even without abstraction rapid pressure decline may already have taken place during drilling without a proper casing;

Phase 2: during the first stage of abstraction, water is produced from clay layers surrounding the sandy horizons largely by a first rearrangement of the clay mineral particles, perhaps from a honeycomb structure to more parallel orientations. Initially high well yields and rapid declines of overpressured conditions can be expected, during this phase of rapid compaction;

Phase 3: the second stage of abstraction will start after a major rearrangement of clay mineral particles has taken place resulting in a slowing down of compaction. Small discharges are to be expected yet still higher than compaction yields thus preventing a recovery of head. Even after static heads have fallen below ground level and the well is abandoned, heads are unlikely to recover due to lack of inflow as in ordinary artesian systems and presumably the effect sealing of the well by strongly compacted clay layers.

In summarizing the major characteristics of the artesian wells in the coastal lowlands, it can be said that these self-flowing wells are driven by hydrostatic excess pressures in clayey sediments subjected to loading from the overburden. Equilibrium conditions in which the load is carried by the grain skeleton has not yet been attained in these low permeability clays. Due to the low permeabilities, the irreversible effect of deflating such an overpressured groundwater body by an artesian well is active on a very local scale.

VIII. SYNTHESIS

In this final chapter it will be shown that all the elements of geology, geomorphology and geological evolution during the Tertiary and Quaternary periods are related in varying degrees to the shape, sediment filling history and later deformation of the Quaternary basins under the present-day coastal lowlands and the Java Sea. A proper understanding of the groundwater flow systems and distribution patterns of hydrochemistry is virtually impossible without contemplating the geology and tectonics in a broad peripheral zone along the southern margin of the coastal lowlands. As may have become apparent in the foregoing chapters, the general hydrogeological framework of the coastal lowlands and distribution of widely varying groundwater qualities deviates strongly from the classical concept of coastal aquifers with dynamic equilibria along a sharp fresh-salt water interface. One is instead faced with a 200 to 300 m thick principally argillaceous Quaternary sediment pile, in which the strata continue far to the north under a very shallow epicontinental Java Sea. The clay and silt strata which originated in shallow marine-, near-shore-, fluvial flood plain- and alluvial/volcanic fan environments possess hydraulic permeabilities which can be classified as poor to very poor. With exception of the alluvial/volcanic fan environment, strongly mineralized pore waters are fixed in the sediments laid down in the remainder. These strongly mineralized groundwaters are even found in terrestrial sediments tens of kilometers from the present-day coast at altitudes which have never been reached by higher sea levels.

Well-defined regionally extending aquifers are lacking and deep wells tap groundwater at various depths from thin sandy clay- or silty layers encased in less permeable layers, which at first sight are difficult to correlate laterally. Considered at a region scale, statistical analysis of the distribution of well depths, in particular those of tube wells, indicated the presence of at least three regionally consistent horizons which are characterized by a significant probability of penetrating those thin permeable layers. Under humid tropical climatic conditions deposition in the flood plains and marine environments is dominantly fine-grained, i.e. clays and silts. Horizons containing deposits of coarser materials are thought to be associated with the periods of appreciably drier climatic conditions and low global sea levels which existed during Pleistocene glacials. Radically different ETA systems (Erosion-Transport-Accumulation) are active during drier climatic conditions with rainfall concentrated in periods of only a few month. Mechanical rock disintegration, increased wind activities and episodic floods giving rise to braided river and sheet flood deposits must have dominated the landscape forming processes during drier climatic conditions. Geological and morphological evidence is presented in the early chapters to support the hypothesis long disputed by botanists of important Pleistocene climatic fluctuations even in Indonesia. Another deposition mechanism to explain the presence of coarser materials so far from the hinterlands is regional volcanic outbursts, though during dry climatic conditions such materials are in fact likely to be transported much further.

The setting of the coastal lowlands closely fits the larger tectonic framework of Java, which finds its origin in the process of subducting the Indian oceanic plate beneath the island accompanied by the generation of ascending magma diapirs. Global reorganizations of mid-oceanic spreading centres in the mosaic of mega-plates, as occurred during the Tertiary, will therefore inevitably affect sedimentation patterns and volcanic activities on Java. The remarkably quiescent interval during much of the Eocene and Oligocene epochs, devoid of magmatic activity in the belt where present-day Java is located, is attributed to a global reorganization of mega-plate boundaries. During active oceanic plate subduction a cycle in regional sedimentation patterns, or 'magmatic island arc loop', can be recognized consisting of (in chronological order) uplift, regional magmatic activity, marginal basin formation, basin filling to continental settings, and so on.

The island of Java can be divided into more or less equal sized structural compartments, with fairly constant widths of about 200 km and bounded by deep-seated N-S trending transverse faults. These transverse faults have their continuation into the mosaic of high offshore basement blocks and basins in the Java Sea. The faults are thought to have originated during revival of oceanic plate subduction at the end of the Oligocene epoch, coinciding with the geological birth of Java. With this concept of structural compartmentalization of Java a wide variety of structural, magmatic and morphological features, which change abruptly crossing the major transverse faults, are easily explained. The northern coastal lowlands with their conspicuous shape, broad with major delta development in West Java (Zone II, see Fig. 4.3) but narrowing abruptly when entering Central Java (Zone III), fits remarkably well into this concept of structural compartmentalization. Considerably higher sediment loads are derived from the provenance areas in West Java which features a double row of volcanoes, complemented by greater degree uplift, as compared to the single row in Central Java. The tectonics along the southern margin of the lowlands, the sedimentary facies of Tertiary strata in the hinterlands and the magmatic development during the Pleistocene also differ between West- and Central Java and thus between zones II and III. The same applies to the geological differences between zones III and IV. Concave normal faults are found in the coastal lowlands as secondary tectonic reactions to the major transverse faults between West- and Central Java. These parallel concave normal faults in turn affect the sub-regional groundwater flow systems by creating topographical steps; for example near the town Tugu in kabupaten Indramayu.

The southern margin of the coastal lowlands partly covers the major tectonic hinge zone along the northern flank of the Java geanticline. The hinge zone consists of a system of deep en-échelon faults separating the uplifted geanticline from the on- and offshore subsided Tertiary and Quaternary sedimentary basins. As a secondary gravitational reaction to these sets of normal faults, northward directed outward sliding movements occurred which converted the en-échelon faults into toppled-over normal faults. The gravity induced gliding tectonics have produced a series of upthrust faults, imbricated structures and décollement in the sedimentary epiderm of plastic clayey strata, accompanied by asymmetrical folds and various kinds of drag structures. The degree of deformation rapidly increases near the hinge zone and in certain areas (kabupaten Brebes) large km-sized slabs have become detached and slid to the north. It can be deduced from the deformation and tectonic styles present in the hinterlands along the lowland southern margin that these structures continue under the lowland margins. Except for some broad faulted culminations they then grade into the relatively undeformed and flat-laying on- and offshore Tertiary strata. In broad outline, the structures along the southern margin of the coastal lowlands in zones II and III are caused by a combination of uplifts of the geanticline, starting at the end of the Pliocene and subsidence on the northern side of the hinge zone, most probably as a result of volumetric compensation for ascending magmas which culminated towards the Middle Pleistocene. Superimposed on these hinge zone structures are local features consisting of radial outward gliding structures produced as a reaction to volcanic cone collapse. Tectonic movements along the hinge zone appear to have taken place continuously up to the present, implying that Quaternary sediments in the southern periphery of the coastal lowlands have been also subjected to deformation.

Although the northern coastal lowlands of Java appear to be almost featureless at first sight, statistical analyses of terrain slope direction and magnitude vectors have disclosed six well-defined clusters, coinciding with the following morphological units :

MCU 1 :	Holocene coastal plain/deltaic plain and lower parts of flood plain belt with tendency for NNE slope directions;
MCU 2 :	southern parts of flood plain belt and valleys incised in Late Pleistocene land surfaces, tendencies for N dipping slopes;
MCU 3 :	dissected Late Pleistocene land surfaces and those covered by Holocene piedmont deposits, constituting the southern margin of the coastal lowlands. Small variability in NNE dip;
MCU 4 :	landforms on volcanogenic fans and aprons, either underlain by the Gintung Formation or originating from Ciremai volcano, mainly in Cirebon;
MCU 5 :	Balapulang volcanogenic fan and piedmont plains around radial gravity sliding structures of Slamet volcano in Tegal;
MCU 6 :	Holocene coastal plain/deltaic plain and lower parts of flood plain belt with variable trends and plunges of slope vectors.

An easterly directed drainage system existed during the last glacial at the end of the Pleistocene when the entire Sunda shelf was dry. Slope vectors of the Late Pleistocene Volcanic Fan Formation, which formed the landscape during the last glacial and those of the Holocene piedmont plains overlying the Late Pleistocene land surface, all show a distinct NNE direction with small standard deviation. This slope vector trend reflects the original terrain slope direction of the land surface during the last glacial. Holocene deposits on top of this Late Pleistocene land surface (morphological units 1 and 6) consist of a typical sequence of shallow marine clays at the base overlain by flood plain clays and silts with intercalations of near-shore deposits. Due to the maximum sea level attained during the Holocene (4,500 a BP) of about 4 to 6 m above present-day mean level in this part of the world, marine clays are absent from higher parts of the Late Pleistocene surface (morphological unit 2).

Morphological zoning of the lowlands is of paramount importance in comprehending groundwater flow systems in these coastal areas. The main theme of this thesis is to show that groundwater flow systems in the northern coastal lowlands are driven only by those morphological units which possess a significantly higher terrain slope than neighbouring ones. Earlier chapters have described the groundwater qualities present under morphological units with a nearly flat terrain slope, such as found in the young Holocene coastal plain/deltaic plain belt. Groundwaters in these units 1 and 6 are largely saline NaCl types with maximum electrical conductivity values of about 10,000 μmhos/cm. This type of saline groundwater is probably also present in the deeper layers under the present-day Java Sea, as indicated by the chloride contents of deep groundwaters beneath the small islands in Jakarta Bay and very young deltaic areas. It is assumed that this NaCl type of groundwater is a reaction series end-member and is present in all stagnant parts of the Quaternary sediments under the Java Sea and young deltaic areas. Although characterized by the NaCl type, the salinity is still far below that of pure Java Sea water, but might also be the result of flushing processes during glacial low sea levels. These flushing processes are likely to take place at a very slow rate, since the surface terrain slope during the last glacial is less than 0.5 m/km in those parts beneath the present-day Java Sea. This implies that originally a saline NaCl type of groundwater was found in the Quaternary sediments which are later flushed by local groundwater flow systems. The following morphological elements and geological processes give rise to elevated and sloping topographies, which in turn may drive groundwater flow systems :

1) Late Pleistocene land surfaces such as found on the Late Pleistocene Volcanic Fan Formation in West Java and those covered by a thin veneer of Holocene piedmont deposits (morphological unit 3);
2) Late Pleistocene/Early Holocene volcanogenic fans and mudflows of radial shape which flowed into the coastal lowlands, such as the famous Balapulang fan and the lahar flows from Tangkuban Perahu volcano (morphological unit 5)[1];
3) normal faulting along the major hinge zone without secondary gravitational reactions, such as found in the Lower Pleistocene fairly permeable volcanoclastic Damar Formation near Weleri and Semarang;
4) normal faulting, transverse to the major structural trends, leading to distinct topographical steps as found in kabupaten Indramayu near Tugu;
5) upthrusting of Quaternary sediments in the coastal lowlands by gravitational gliding movements in the Tertiary hinterland, resulting from a collapse of a volcanic cone or diapiric upbulging of a volcanic foot;

As shown in the various cross sections through the coastal lowlands these morphological elements and geological processes are of paramount importance in generating groundwater flow systems which may flush the deeper strata in the Quaternary basins, once containing saline pore waters. On the other hand the presence of these elements may not always guarantee the generation of deeper groundwater flow, such as in cases where impervious Tertiary strata are found at shallow depth. Nevertheless, the study of morphological and geological aspects of the coastal lowlands and adjacent hinterlands remains of paramount importance in unravelling the peculiar distribution of hydrochemistry and flow systems.

Six major coastal lowland settings found in the studied area are shown in Fig. 8.1. Groundwater flow pattern in the situation of a coastal plain/deltaic plain dominated setting is given by Fig. 8.1a. Groundwater circulation occurs mainly in the most southern narrow strip, leaving vast semi-stagnant bodies of groundwater in the broad coastal- and deltaic plains. The flux of a branch of Flow System I beneath the semi-stagnant bodies is usually too small to effectuate flushing. An entirely different situation is met in lowlands which are dominated by a broad belt of the exposed Late Pleistocene Volcanic Fan Formation and a young narrow strip of newly accreted coastal- and deltaic plains (Fig. 8.1b). In these settings a second local flow system may be present. Semi-stagnant groundwater bodies are absent and Flow System I generates an important sub-regional branch which emerges through a window in the narrow coastal plain strip. The deeper groundwaters are fresh $NaHCO_3$ and even $CaHCO_3$ types. Higher fluxes of groundwater are generated if Holocene lahar flows and volcanogenic fans are deposited on the Late Pleistocene Volcanic Fan Formation, as shown in Fig. 8.1c.

1 Although located outside the study area, striking examples of volcanogenic fans which reached the Java Sea are found in the Jakarta Bogor area. At least three large coalescing fans can be recognized from satellite images.

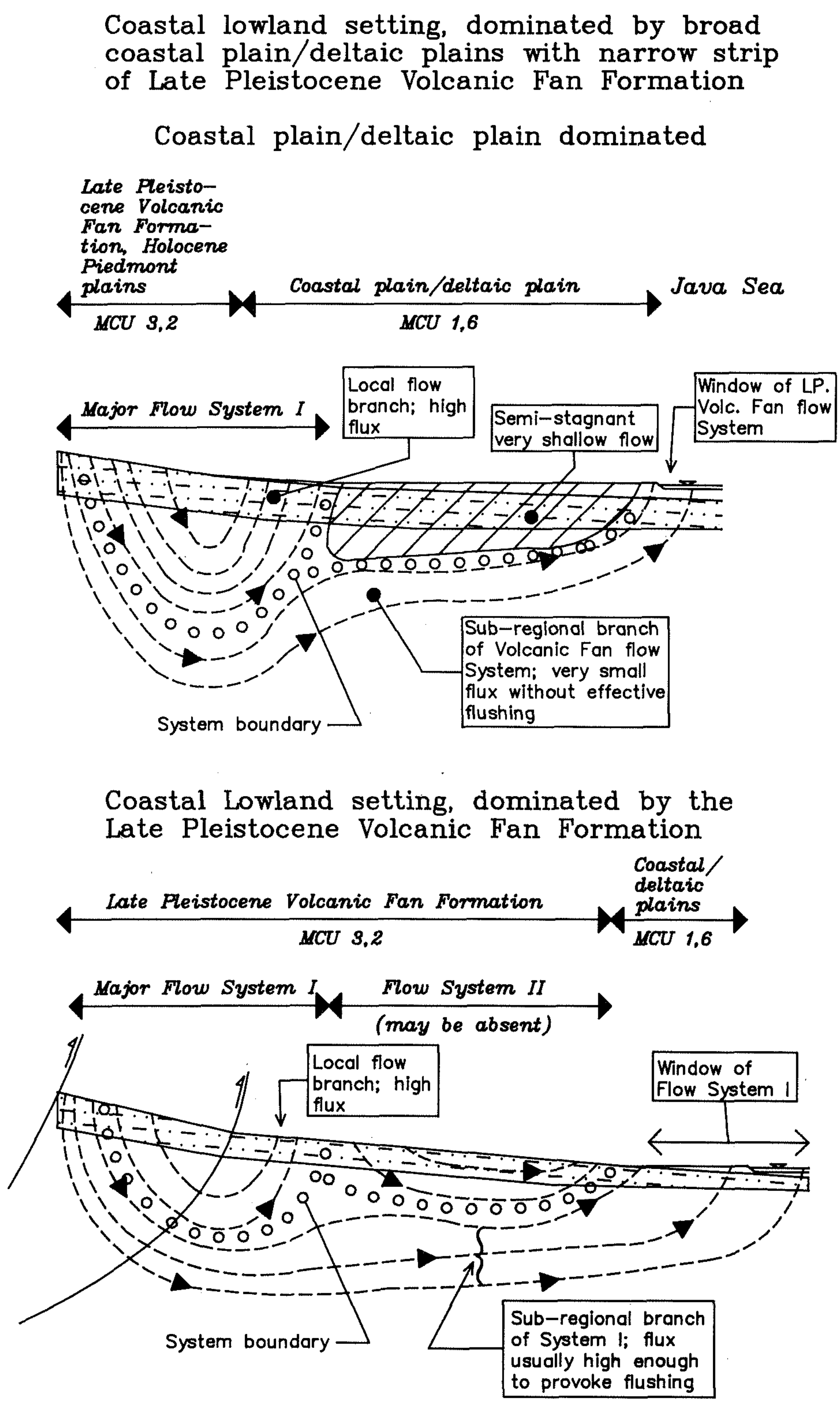
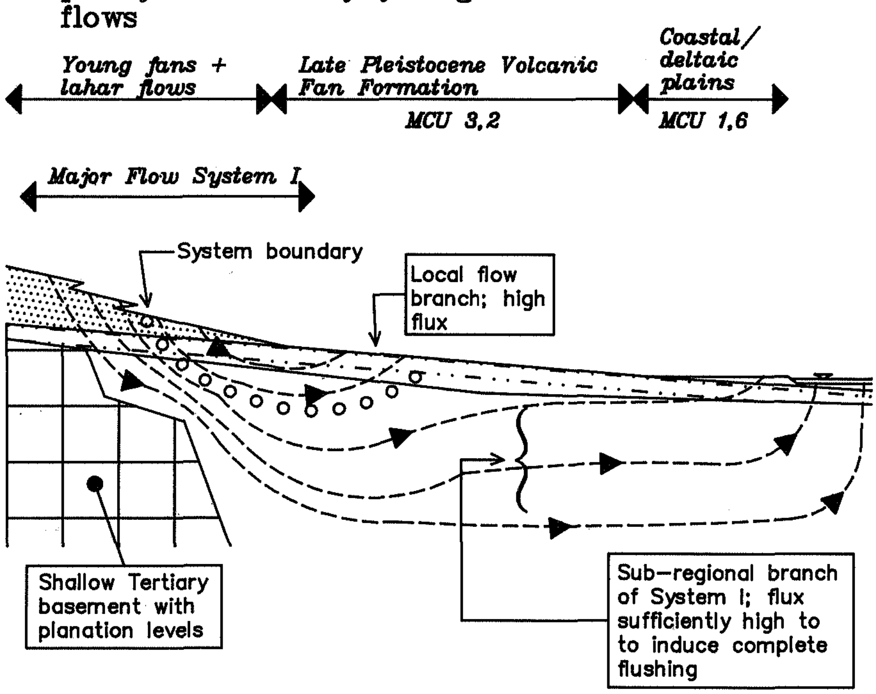


Fig. 8.1ab Summary of major morphological and geological elements in the coastal lowland framework and their effects on groundwater flow pattern.

Coastal Lowland setting, dominated by the Late Pleistocene Volcanic Fan Formation partly overlain by younger fans and lahar flows



Coastal lowland, dominated by broad coastal plain/deltaic plain with narrow Holocene piedmont plain

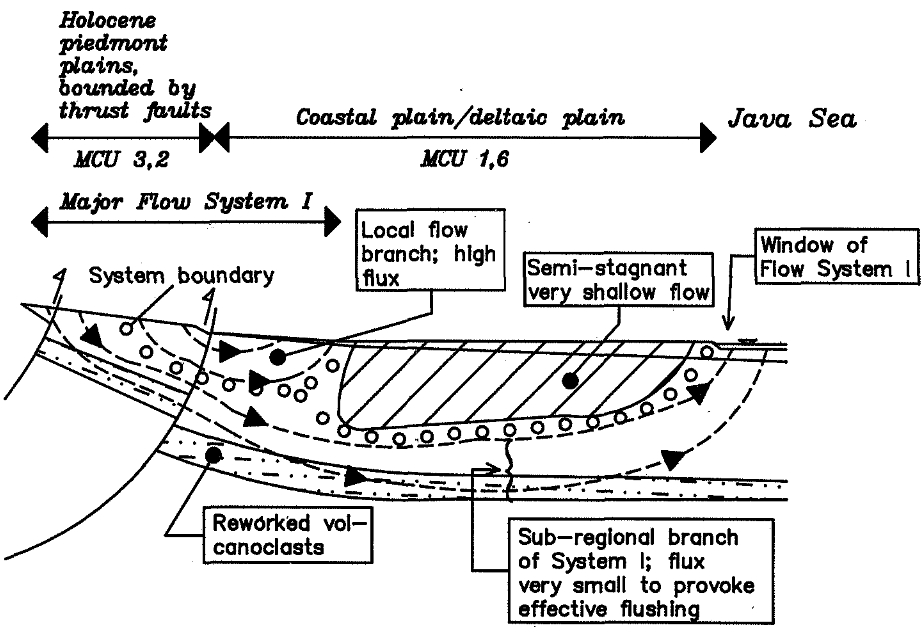
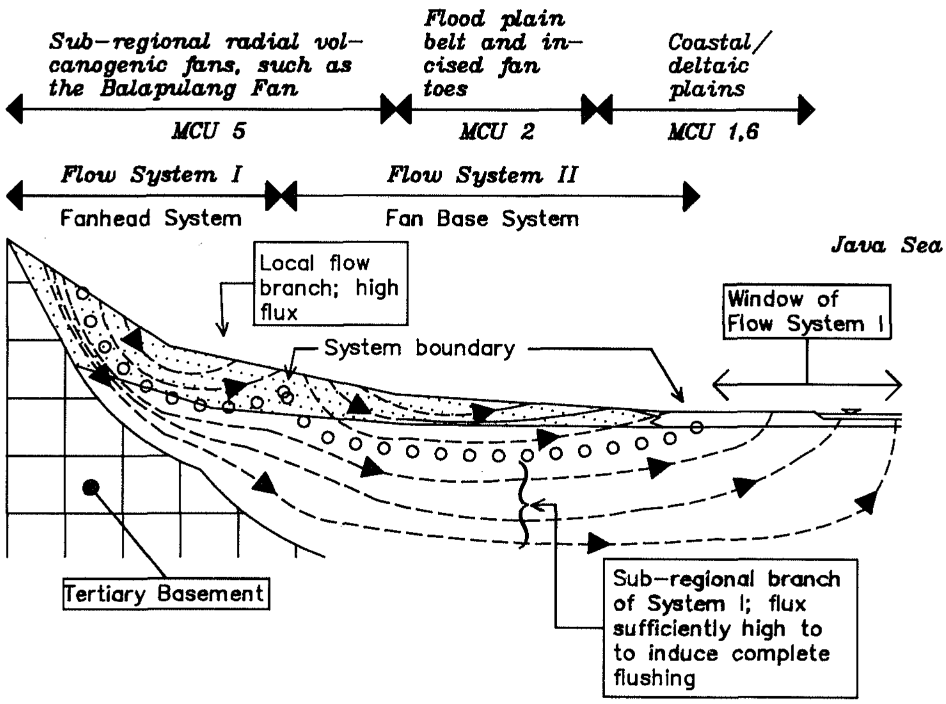


Fig. 8.1cd Summary of major morphological and geological elements in the coastal lowland framework and their effects on groundwater flow pattern.

Coastal Lowland setting, dominated by a sub-regional radially shaped young volcanogenic fan



Coastal Lowland setting, dominated by a shallow Tertiary basement with block faulting

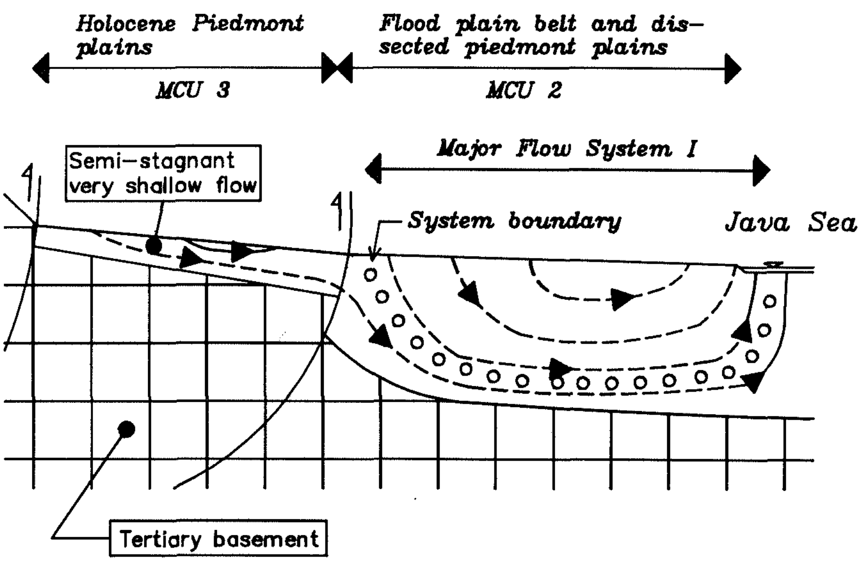


Fig. 8.1ef Summary of major morphological and geological elements in the coastal lowland framework and their effects on groundwater flow pattern.

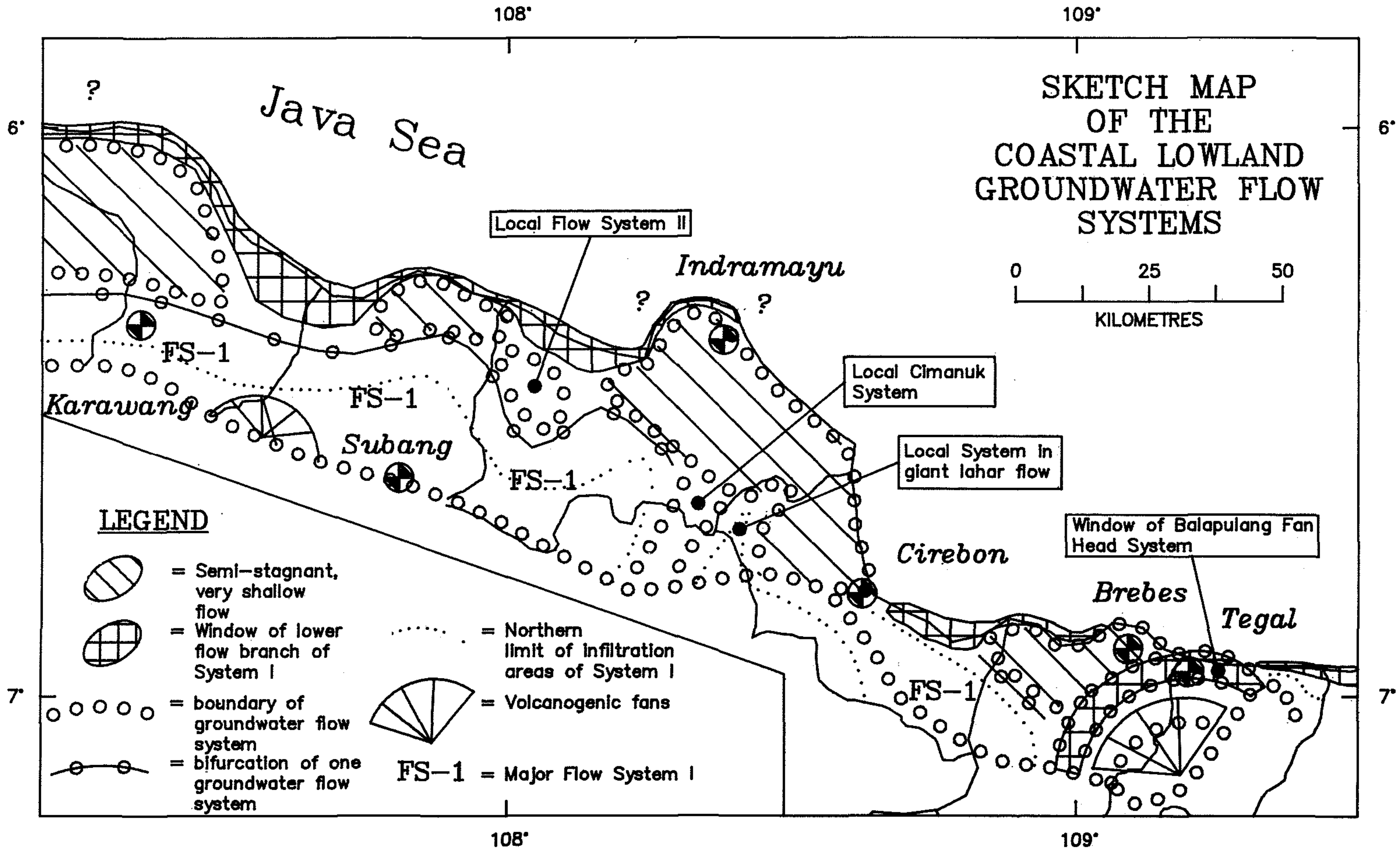


Fig. 8.2 Location sketch map of the various groundwater flow systems in the studied coastal lowlands.

The setting in Fig. 8.1d resembles that in Fig. 8.1a with the difference that Flow System I is driven by a Holocene piedmont plain which overlies the Late Pleistocene/Early Holocene land surface. Large volcanogenic fans such as the Balapulang fan in kabupaten Tegal may exhibit two flow systems as depicted Fig. 8.1e. The sub-regional branch of Flow System I which flows under the superposed Flow System II, emerges through a broad window in front of the fan base. Flushing by this sub-regional branch is sufficient, in the case of Balapulang fan, to attain $NaHCO_3$ types in the deeper groundwater. Groundwater flow patterns controlled by the geological structure under the coastal lowlands is displayed in Fig. 8.1f. For the case of shallow depth to the Tertiary basement as assumed in the lowlands in eastern Tegal, a major groundwater flow system is pushed towards areas with a sudden deepening basement. This situation can be expected on the northern side of the upthrust faults.

Based on cross sections through the various lowland kabupatens a sketch map has been compiled (Fig. 8.2) which summarizes assumed boundaries and positions of the groundwater flow systems in this northern coastal area of Java.

LIST OF FIGURES

Fig. 1.1	General location map.
Fig. 1.2	The principal terrain types on Java.
Fig. 1.3	Major drainage systems in the northern part of Java.
Fig. 1.4	Population densities according to the 1961, 1971 and 1980 national censuses.
Fig. 2.1	Toth's (1962) vertical model for groundwater flow.
Fig. 2.2	Hierarchy of water related systems, according to Engelen (1986).
Fig. 2.3	Major earth and water systems.
Fig. 3.1	Major lithospheric plates in the Indonesian Archipelago.
Fig. 3.2	Principal tectonic elements of the Java subduction system, partly after Batchelor (1979) and Hamilton (1979).
Fig. 3.3	Classical diagram of the Java subduction system.
Fig. 3.4	Melange terrains and inferred limit of continental crust during Late Cretaceous and Early Tertiary, modified after Hamilton (1979).
Fig. 3.5	Interlinked earth systems in magmatic island arcs.
Fig. 4.1	Location map of the Pleistocene marine terraces.
Fig. 4.2ab	Field sketches of the Pleistocene fossil shoreline deposits south of village of Sigentong; see Fig. 4.1.
Fig. 4.3	Major structural features and surmised structural zoning in West- and Central Java.
Fig. 4.4	Location map of the geological cross sections shown in Fig. 4.5a to 4.5f.
Fig. 4.5ab	Cross sections near the towns of Subang and Tomo in West Java.
Fig. 4.5cd	Cross sections near the villages of Waled and Karangbale in Central Java.
Fig. 4.5ef	Cross sections near the village of Gongseng and town of Weleri in Central Java.
Fig. 4.6	Field sketch of tilted reef limestones at Prupuk.
Fig. 4.7	Schematic representation of the various stages of the Prupuk reef limestones.
Fig. 4.8	Diagram showing the interaction of tectonic movements and the system of extensive low-relief surfaces.
Fig. 5.1	General sedimentation model for the coastal lowlands.
Fig. 5.2	General construction of small diameter tube wells as found in the coastal lowlands.
Fig. 5.3	Location of the six studied kabupatens.
Fig. 5.4	Depth-frequency distribution for all tube wells (artesian + pumped, N = 1,584).
Fig. 5.5ab	Depth-frequency distributions for (a) all artesian with depth > 12 m (N=405, upper diagram) and (b) all hand-pumped tube wells with depth > 12 m (N=733, lower diagram).
Fig. 5.6ab	Log differences of class frequencies versus depth for (a) all artesian tube wells (N=405, upper diagram) and (b) the entire tube well population (N=1584, lower diagram).
Fig. 5.7	Observed and expected frequencies of artesian tube well depths (depth > 12 m, N=405).
Fig. 5.8	Distribution of tube well types for the three depth clusters.
Fig. 6.1	Map showing the slope vectors derived by fitting two-dimensional surfaces to altitude benchmarks within square grid cells measuring 6 to 10 km.
Fig. 6.2	Histogram of slope vector trends in West- and Central Java expressed in degrees west (-) or east (+) from north (0).
Fig. 6.3	Histogram of the plunge component in slope vectors.
Fig. 6.4	The six groups found by cluster analysis in the sample of slope vectors and their regional occurrence. See also Table 6.4 for more detailed descriptions of physical setting for the groups.
Fig. 6.5	Typical coastal lowland cross section showing the sedimentary units embedded in a basin framework (inset modified after Koesoemadinata et al., 1985, Janssen et al., 1985 and Rimbaman, 1986).

Fig. 6.6 Diagram showing the assumed sequence of geological developments in the coastal lowlands from the last but one interglacial to the last glacial period, prior to the Holocene developments shown in Fig. 6.5.
Fig. 7.1ab Average annual precipitation depths (mm) for the coastal lowlands in West Java (a) and Central Java (b), modified after I Made Sandy (1982).
Fig. 7.2ab Average monthly rainfall depths (a) and average yearly rainfall depths (b) during the period 1970 to 1979 for recording stations in the coastal lowlands.
Fig. 7.3 General physical setting of kabupaten Karawang.
Fig. 7.4 Division of kabupaten Karawang into major groundwater provinces.
Fig. 7.5 General legend for the hydrochemical cross sections.
Fig. 7.6 Hydrochemical cross section Karawang I (see Fig 7.5 for general legend).
Fig. 7.7 Geometric and hydraulic input parameters, representing cross section Karawang I, for the vertical groundwater model FLOWNET (K_h=horizontal hydraulic conductivity, K_v=vertical hydraulic conductivity).
Fig. 7.8 Hydrochemical cross section Karawang II (see Fig. 7.5 for general legend).
Fig. 7.9 Hydrochemical cross section Karawang III (see Fig. 7.5 for general legend).
Fig. 7.10 General physical setting in kabupaten Subang.
Fig. 7.11 Division of kabupaten Subang into major groundwater provinces.
Fig. 7.12 Lithological logs of the deep wells Pamanukan 1, situated about 10 km south of Pamanukan along the road Pamanukan-Subang and Pamanukan 2, near the town itself. Lithology simplified and modified after Djoehanah (1984).The three statistically derived tube well depth clusters are represented as 68% confidence intervals around the mean.
Fig. 7.13 Hydrochemical cross section Subang I (see Fig. 7.5 for general legend).
Fig. 7.14 Hydrochemical cross section Subang II (see Fig. 7.5 for general legend).
Fig. 7.15 Hydrochemical cross section Subang III (see Fig. 7.5 for general legend).
Fig. 7.16 Hydrochemical cross section Subang IV (see Fig. 7.5 for general legend).
Fig. 7.17 General physical setting in kabupaten Indramayu.
Fig. 7.18 Division of kabupaten Indramayu into major groundwater provinces.
Fig. 7.19 Hydrochemical cross section Indramayu I (see Fig. 7.5 for general legend).
Fig. 7.20 Hydrochemical cross section Indramayu II (see Fig. 7.5 for general legend).
Fig. 7.21 Hydrochemical cross section Indramayu III (see Fig. 7.5 for general legend).
Fig. 7.22 Schematic E-W cross section from the Cimanuk river to the Java Sea, showing the characteristic chemical types of groundwater in the various lithological elements. Quaternary geological framework adapted from Janssen & Dam (1985).
Fig. 7.23 Chloride profiles at the end of the dry period (September, 1987) in the flood plain area SE of the town Indramayu.
Fig. 7.24 Stable isotope composition of δ^2H and $\delta^{18}O$ in four samples of shallow groundwater in the flood plain deposits of Cimanuk delta.
Fig. 7.25 General physical setting in kabupaten Cirebon.
Fig. 7.26 The principal geological elements in kabupaten Cirebon.
Fig. 7.27 Division of kabupaten Cirebon into major groundwater provinces.
Fig. 7.28 Hydrochemical cross section Cirebon I (see Fig. 7.5 for general legend).
Fig. 7.29 Hydrochemical cross section Cirebon II (see Fig. 7.5 for general legend).
Fig. 7.30 Hydrochemical cross section Cirebon III (see Fig. 7.5 for general legend).
Fig. 7.31 General physical setting in kabupatens Brebes and Tegal.
Fig. 7.32 Terrain slope vectors (derived in Chapter 6) in kabupatens Brebes and Tegal.
Fig. 7.33 Major tectonic structures in kabupatens Brebes and Tegal.
Fig. 7.34 Division of kabupatens Brebes and Tegal into major groundwater provinces.
Fig. 7.35 Hydrochemical cross section Brebes/Tegal I (see Fig. 7.5 for general legend).
Fig. 7.36 Hydrochemical cross section Brebes/Tegal II (see Fig. 7.5 for general legend).
Fig. 7.37 Hydrochemical cross section Brebes/Tegal III (see Fig. 7.5 for general legend).

Fig. 7.38 Stable isotope composition of δ^2H and $\delta^{18}O$ in samples of shallow groundwater for the piedmont plain deposits in Brebes and Tegal.
Fig. 8.1a,b Summary of major morphological and geological elements in the coastal lowland framework and their effects on groundwater flow pattern.
Fig. 8.1c,d Summary of major morphological and geological elements in the coastal lowland framework and their effects on groundwater flow pattern.
Fig. 8.1e,f Summary of major morphological and geological elements in the coastal lowland framework and their effects on groundwater flow pattern.
Fig. 8.2 Location sketch map of the various groundwater flow systems in the studied coastal lowlands.

LIST OF TABLES

Table 1.1 Areas of irrigated rice fields in Kabupaten Karawang.
Table 1.2 Population densities in the study area, according to national censuses in 1961, 1971 and 1980.
Table 2.1 Earth and water systems and major subsystems.
Table 2.2 Time and scale of various phenomena in the study area.
Table 3.1 Summary of major plate events in the Indian Ocean (after Le Pichon et al., 1985).
Table 3.2 Characteristic Java lithologies and major plate events in the Indian Ocean.
Table 4.1 Major exposed Pleistocene stages in North Java.
Table 4.2 Hypothetical sedimentary environments during the Pleistocene in North Java.
Table 5.1 Quaternary basin history and major geological events.
Table 5.2 Collected well data showing the numbers of wells by type and kabupaten.
Table 5.3 Cluster analysis on artesian tube well depth data with cluster centroid results in m depth.
Table 5.4 Final cluster centroids for all tube well data and pumped tube wells, with depth of centroids in m.
Table 5.5 Results of non-linear least squares fitting of three Gaussian components to the depth data for all artesian tube wells.
Table 5.6 Descriptives of the three sampled clusters in the artesian tube well depth data, based on the results of Table 5.5.
Table 5.7 Results of the Kolmogorov-Smirnov test of normality on depth data for all artesian wells.
Table 5.8 Results of the Kolmogorov-Smirnov normality test on depth data for all artesian wells; clusters 2 and 3.
Table 5.9 One-Way analysis of variance on variable Depth by category variable Cluster for artesian tube well data.
Table 5.10 One-Way analysis of variance on variable Depth by category variable Kabupaten for artesian tube well data.
Table 5.11 One-Way analysis of variance and Kruskal-Wallis tests, for artesian tube well data, on variable Depth by category variable Kabupaten (first group: Brebes, Cirebon, Indramayu and second group: Karawang, Subang, Tegal).
Table 5.12 One-Way analysis of variance, for artesian tube well data on variable Depth by category variable Kabupaten for the first depth cluster (variable Cluster preset at 1), Tegal is omitted.
Table 5.13 One-Way analysis of variance, for artesian tube well data on variable Depth by category variable Kabupaten for the second depth cluster (variable Cluster preset at 2), Cirebon is omitted.

Table 5.14 One-Way analysis of variance, for artesian tube well data on variable Depth by category variable Kabupaten for the third depth cluster (variable Cluster preset at 3).

Table 5.15 Summary of Two-Way analysis of variance (ANOVA) on variable Depth by the category variables Cluster and Kabupaten for artesian, pumped and all types of tube well depth data.

Table 5.16 Summary of One-Way analysis of variance on variable Depth by category variable Kabupaten for each cluster in pumped tube well depth data; depth > 24 m.

Table 5.17 Summary of One-Way analysis of variance on variable Depth by category variables Kabupaten for each cluster in the entire population of tube well depth data; depth > 24 m.

Table 5.18 Summary of One-Way analysis of variance on variable Depth by the category variable Kabupaten on Cluster 2 for the entire population of tube well depth data; depth > 24 m and excluding kabupatens Brebes and Cirebon.

Table 5.19 Summary of One-Way analysis of variance on variable Depth by the category variable Kabupaten on Cluster 2 for the entire population of tube well depth data; depth > 24 m and for only kabupaten Brebes and Cirebon.

Table 5.20 Summary of One-Way analysis of variance on variable Depth by category variable Kabupaten for a group of artesian tube wells between two arbitrary boundaries of 40 and 91 m and a group of wells constituting a combination of Clusters 1 and 2.

Table 6.1 Major statistics of the number of benchmarks and multiple correlation coefficients for the 88 grid cells.

Table 6.2 Plunge clusters in the slope vectors expressed as m/km.

Table 6.3 Major clusters in the slope vectors.

Table 6.4 Correlation between slope vector clusters and morphological coastal lowland (MCU) units in the physical setting.

Table 6.5 Result of discriminant analysis on the six groups in the slope vectors given by Table 6.3.

Table 6.6 Actual- and predicted group membership.

Table 6.7 Summary of hydrogeological units in the coastal lowlands built up by sedimentary units and soil horizons.

Table 7.1 Examples of the main chemical types of groundwaters in the area of slope vector cluster 3, Karawang I.

Table 7.2 Examples of the main chemical types of groundwater in the flood plain clays and silts in the area of morphological unit 3, Karawang I.

Table 7.3 Examples of the main chemical types of groundwater from deeper tube wells in section Karawang I.

Table 7.4 Summary of soil permeability tests in the kabupatens Karawang and Indramayu.

Table 7.5 Examples of the main chemical types of groundwater from section Karawang II.

Table 7.6 Examples of the main chemical types of groundwater from section Karawang III.

Table 7.7 Examples of the main chemical types of groundwater from section Subang I.

Table 7.8 Characteristic chemical types of groundwater in the deeper aquifer horizons from section Subang II.

Table 7.9 Characteristic chemical types of groundwater in the young volcanic materials from section Subang II.

Table 7.10 Characteristic chemical types of deeper groundwater under the Holocene coastal plain in section Subang III.

Table 7.11 Characteristic chemical types of deeper groundwater under the Holocene coastal plain in section Subang IV.

Table 7.12 Characteristic chemical types of deeper groundwater near the village Anjatan in cross section Indramayu I.

Table 7.13 Characteristic chemical types of shallow groundwater in the flood plain clays of Cimanuk delta.

Table 7.14	Averages of ion ratios for 44 samples of shallow groundwater in the flood plain clays of Cimanuk delta belonging to the NaCl and NaMix types. The One-sample Z-test (two-tailed) is used to test whether the average ion ratios of 44 water samples differ significantly from those of standard sea water. The null hypothesis, stating that the mean ion ratio = ion ration of sea water, is accepted if the calculated Z-test statistic falls in the range from -1.96 to +1.96 (5% two-tailed significance level).
Table 7.15	Characteristic chemical types of groundwater in the marine clays and mudstones of the Upper Miocene Halang Formation.
Table 7.16	Characteristic chemical types of shallow groundwater (depth less than 15 m) in the piedmont plain areas of kabupatens Brebes and Tegal.
Table 7.17	Initial static heads above ground level for a number of pre-war large diameter deep wells, as recorded in the 'Jaarboek van het Mijnwezen'.
Table 7.18	Initial static heads above ground level and original chloride contents of wells drilled on small islands in the Bay of Jakarta, as recorded in the 'Jaarboek van het Mijnwezen'.

APPENDIX I

In this Appendix a short review is given of the main features of the hydrochemical classification of Stuyfzand (1986) as used in the thesis. For more details the reader is referred to the original paper, titled : 'A new hydrochemical classification of watertypes; principles and application to the coastal dunes aquifer system of The Netherlands'. Stuyfzand classification is based on a four-level subdivision of the major characteristics of water chemistry. He distinguishes chloride content as a main type, an index for hardness as a type, the dominant cations and anions as a subtype and a correction index for the contribution of sea salt as a class. As an example a 'fresh, moderately hard calciumbicarbonate water with a [Na+K+Mg]-surplus over sea water' would be coded as 'F1-$CaHCO_3$+'. From left to right, the four codes will be discussed briefly in the following :

Main type

The chloride content determines the main type as shown in the following table :

Main type	code	Cl^- mg/l	Main type	code	Cl^- mg/l
fresh	F	<150	brackish-salt	B	10^3-10^4
fresh-brackish	f	150-300	salt	S	10^4-2.10^4
brackish	b	300-10^3	hypersaline	H	>2.10^4

The single letter codes as shown in this table become the first letter of the hydrochemical classification.

Type

Total hardness (mainly Ca + Mg) is used to subdivide the types as follows :

Type	code	total hardness mmol/l
very soft	*	0 - 0.5
soft	0	0.5 - 1
moderately hard	1	1 - 2
hard	2	2 - 4
very hard	3	4 - 8
extremely hard	4	8 - 16
extremely hard	5	16 - 32
extremely hard	6	32 - 64
extremely hard	7	64 - 128
extremely hard	8	128 - 256
extremely hard	9	> 256

Similarly, this single letter code for hardness becomes the second character in the hydrochemical classification.

Subtypes

The division into subtypes based on the dominant cations and anions (based on meq/l) follows more or less the traditional appelations as found in other classification systems. Examples of common subtypes are : $NaHCO_3$, CaCl, $CaSO_4$, $MgHCO_3$, $CaHCO_3$, NaCl, NaMix, CaMix, MgCl etc.

Classes

Stuyfzand devised a new parameter for the sum of Na, K and Mg in meq/l corrected for a contribution of sea salt. The coding, which forms the latter character of the hydrochemical classification, is as follows :

Class	code	condition meq/l
{Na+K+Mg} deficit [1]		{Na+K+Mg} corr < - Cl
{Na+K+Mg} equilibrium	0	Cl <= {Na+K+Mg} corr <= + Cl
{Na+K+Mg} surplus [2]	+	{Na+K+Mg} corr > - Cl

1 = often pointing at a (former) salt water intrusion
2 = often pointing at a (former) fresh water encroachment

APPENDIX II

SUMMARY OF THE GROUNDWATER HYDROCHEMISTRY
(Analytical concentrations in mg/l.)

Section Karawang I

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
11	120	1200	8.0	16.6	2.5	179.7	2.3	298.7	166.3	8.2	-4.5%	f0-NaHCO3+
12	134	1200	8.2	12.4	2.4	179.8	1.4	298.7	131.3	6.1	-0.3%	F*-NaHCO3+
15	144	1400	7.9	10.4	3.8	185.2	1.6	238.9	228.6	8.2	-8.3%	f*-NaCl 0
16	120	1400	8.2	12.4	2.4	196.2	1.6	253.9	216.9	8.2	-5.3%	f*-NaCl +
19	120	2100	7.9	24.9	1.0	353.0	2.7	119.5	500.9	8.2	1.5%	b0-NaCl 0
21	45	1450	7.7	66.3	1.5	229.4	8.0	89.6	376.4	1.2	5.8%	b1-NeCl 0
21	2	4500	6.9	227.8	199.4	531.6	14.0	324.5	1010.6	492.8	7.5%	B4-MgCl +
22	48	1400	7.8	101.6	1.8	136.6	11.2	89.6	368.6	4.1	-2.2%	b2-NaCl -
23	40	1450	7.8	66.3	19.9	196.2	8.5	89.6	364.7	8.2	6.9%	b2-NaCl 0
24	84	2350	7.7	54.1	32.4	251.4	12.8	283.7	481.5	4.1	-4.8%	b2-NaCl 0
25	114	6200	7.8	91.1	44.9	723.9	10.5	209.1	1384.1	4.1	-3.1%	B3-NaCl -
26	102	3600	7.4	45.6	29.9	490.4	8.5	298.7	893.9	8.2	-7.1%	b2-NaCl 0
27	102	3400	7.4	51.8	26.2	504.1	8.0	253.8	816.1	8.2	-0.9%	b2-NaCl 0
28	78	3800	7.3	99.4	47.4	531.6	10.0	119.5	1065.1	8.2	0.1%	B3-NaCl -
29	48	10000	6.7	1118.1	740.7	2391.1	33.5	119.5	6305.0	184.0	9.4%	B6-MgCl -
30	54	2250	7.9	37.3	17.5	325.5	5.5	179.2	512.6	6.1	0.2%	b1-NaCl 0
31	114	3700	7.8	49.7	24.9	504.1	6.0	209.1	967.8	8.2	-7.5%	b2-NaCl -
33	126	1600	7.9	16.6	10.0	298.1	3.5	298.7	314.2	4.1	3.0%	b0-NaCl +
44	78	3000	7.7	24.9	24.9	435.4	9.5	298.7	714.9	6.1	-5.7%	b1-NaCl 0
48	90	2800	7.5	37.3	17.4	462.9	8.5	298.7	734.4	8.2	-4.3%	b1-NaCl 0
50	90	3200	7.6	43.2	29.3	477.9	11.7	268.8	777.2	4.1	-1.5%	b2-NaCl 0
52	96	3400	7.7	46.2	27.8	467.7	9.9	324.5	722.7	4.1	-1.2%	b2-NaCl 0
55	120	580	8.4	8.7	5.6	114.3	1.5	261.0	42.2	11.2	1.8%	F*-NaHCO3+
139	30	450	6.2	34.5	19.1	10.2	0.1	119.5	47.6	12.3	2.4%	F1-CaHCO30
141	50	680	6.3	73.4	17.3	53.8	7.3	238.9	41.8	110.4	1.4%	F2-CaHCO3+
171	150	4000	7.5	51.8	16.5	784.0	5.5	179.2	1201.3	4.1	1.7%	B1-NaCl 0
171	120	2200	7.7	29.0	7.5	300.5	4.2	283.7	485.4	8.2	-9.7%	b1-NaCl 0
172	114	1700	8.2	23.3	14.0	286.1	6.4	298.7	372.5	4.1	-1.9%	b1-NaCl +
173	90	2350	7.8	24.9	7.5	306.0	5.5	298.7	434.8	8.2	-6.2%	b0-NaCl 0
174	12	1500	7.1	167.6	46.6	123.7	1.1	503.4	160.5	202.3	1.8%	f3-CaMix +
175	3	1500	7.4	133.6	38.9	190.7	0.2	522.7	175.6	191.1	1.9%	f3-CaMix +
177	3	2100	7.5	91.0	41.3	350.4	0.5	612.6	188.9	337.2	1.8%	f2-NaMix +
178	3	3800	7.0	292.7	162.2	289.5	2.3	422.8	759.2	500.2	2.3%	b4-CaCl 0
179	120	620	8.7	7.7	2.8	139.2	2.2	332.3	37.7	2.8	1.2%	F*-NaHCO3+
180	3	6900	7.1	702.6	325.7	378.5	8.3	660.3	1405.1	1146.6	2.7%	B5-CaCl 0
181	120	650	8.7	7.2	6.2	122.3	2.4	280.2	60.4	1.5	-0.6%	F*-NaHCO3+
182	138	560	8.0	52.7	19.9	47.8	4.5	308.8	22.7	28.1	1.4%	F2-CaHCO3+
183	4	1750	6.6	148.5	84.1	74.4	3.8	220.7	279.5	258.6	2.3%	f3-CaMix 0
184	4	1800	6.5	241.3	24.0	122.3	7.0	294.5	306.0	286.7	0.2%	b3-CaMix 0
185	18	1600	6.9	113.4	62.8	158.0	3.3	437.1	151.1	264.2	2.5%	f3-CaMix +
186	4	1100	7.0	121.9	62.4	11.1	1.8	237.5	173.7	123.6	1.6%	f3-CaMix 0
187	3	2000	6.4	244.0	102.7	50.7	0.6	294.5	336.2	365.3	2.1%	b4-CaMix 0
188	12	4500	7.9	378.8	163.6	544.0	1.7	855.0	914.1	725.1	1.1%	b5-CaMix +
189	1	2250	7.0	119.9	25.6	394.1	1.8	655.3	306.0	258.6	1.0%	b3-NaMix +
190	1	1800	7.5	115.0	76.7	235.7	2.3	465.6	211.5	376.6	2.1%	f3-MgMix +
191	120	1200	7.9	23.9	10.6	197.1	1.1	223.2	230.4	5.6	1.9%	f1-NaCl +

Section Karawang II

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
62	2	1100	7.9	126.1	56.7	44.4	2.5	375.1	113.3	151.7	1.8%	F3-CaMix +
68	114	800	8.1	22.6	2.9	141.2	3.7	223.2	128.4	5.6	1.4%	F0-NaMix +
69	114	900	8.1	14.5	4.5	200.3	2.8	166.2	177.5	16.9	10.0%	f0-NaCl +
129	12	500	6.5	48.8	14.6	29.9	0.3	209.1	22.3	28.6	3.1%	F1-CaHCO3+
152	12	350	6.3	49.7	5.0	13.0	1.0	119.5	45.7	24.5	-3.8%	F1-CaHCO30
156	2.5	100	5.5	13.3	4.8	3.5	0.3	29.9	14.6	12.3	2.4%	F0-CaMix 0

158	21	300	6.7	31.8	14.6	6.6	0.9	149.3	12.6	6.1	2.8%	F1-CaHCO3+
159	1	650	6.3	41.9	19.8	58.4	13.7	119.5	123.5	45.0	1.8%	F1-CaCl 0
162	1	850	6.1	44.6	23.0	91.7	0.7	149.3	131.3	83.8	1.4%	F2-CaMix +
193	93	600	8.7	9.6	3.5	93.0	3.0	251.7	56.7	5.6	-8.9%	F*-NaHCO3+
194	132	1100	8.6	6.7	3.4	208.1	2.4	228.2	190.7	11.2	2.0%	f*-NaCl +
195	96	750	8.3	19.3	4.3	180.8	4.3	328.0	70.0	90.0	0.4%	F0-NaHCO3+
196	2	1900	6.9	160.3	89.6	122.8	5.2	636.7	268.2	89.9	2.4%	f3-CaHCO3+
197	2	1100	7.0	133.8	55.4	4.3	3.6	456.3	92.5	56.2	1.1%	F3-CaHCO3+
198	84	630	8.7	14.5	9.8	112.5	3.0	256.7	66.1	20.0	0.1%	F0-NaHCO3+
199	102	690	8.7	9.6	2.1	102.8	1.9	189.7	75.6	1.5	-1.0%	F*-NaHCO3+
200	96	670	8.1	7.2	7.6	122.3	4.1	237.5	77.4	5.6	1.7%	F*-NaHCO3+
201	110	850	8.7	9.6	7.4	180.8	4.7	175.5	164.3	5.6	8.7%	f0-NaCl +
202	85	710	8.4	12.1	8.6	161.3	4.0	266.0	83.1	80.0	0.4%	F0-NaHCO3+
203	120	1250	8.5	16.3	4.5	214.4	2.3	142.0	268.2	11.2	2.1%	f0-NaCl 0
204	2	1300	7.7	41.8	42.8	152.4	9.0	294.5	249.3	5.6	2.0%	f2-NaCl +
205	96	900	8.4	7.3	5.6	166.2	2.3	199.6	158.6	5.6	1.5%	f*-NaCl +
206	48	570	8.7	9.6	4.8	105.0	3.0	299.5	37.8	5.6	-4.9%	F*-NaHCO3+

Section Karawang III

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
120	24	800	8.1	46.9	15.8	96.4	2.1	149.3	174.1	16.4	1.2%	f1-NaCl 0
123	72	400	8.0	16.6	7.5	80.8	2.0	179.2	22.3	32.7	8.3%	F0-NaHCO3+
144	80	540	8.2	10.4	3.7	102.7	2.1	238.9	34.0	12.3	2.0%	F*-NaHCO3+
145	90	10000	7.1	738.1	614.8	1851.0	20.5	358.4	5019.1	764.8	1.5%	B6-MgCl -
146	90	800	7.9	12.4	7.4	146.7	3.0	179.2	135.2	6.1	5.5%	F0-NaCl +
147	80	600	8.2	8.4	7.1	100.7	1.5	194.1	69.0	8.2	1.2%	F0-NaHCO3+
148	84	600	8.0	14.5	3.7	124.7	2.5	298.7	37.9	4.1	3.7%	F0-NaHCO3+
149	78	600	8.0	4.5	2.2	43.1	0.7	41.8	41.8	10.2	5.1%	F*-NaCl +
166	40	800	7.7	51.8	13.8	113.7	3.1	119.5	170.2	20.4	9.8%	f1-NaCl 0
167	36	780	7.8	39.8	8.0	104.1	2.6	119.5	150.7	40.9	1.2%	f1-NaCl 0
167	132	480	8.5	6.9	0.8	90.1	0.7	149.3	61.3	4.1	1.0%	F*-NaHCO3+
168	126	480	8.2	6.6	1.0	98.5	0.8	164.3	61.3	8.2	1.3%	F*-NaHCO3+
169	140	480	8.8	3.1	1.8	106.8	0.5	179.2	57.4	12.3	1.5%	F*-NaHCO3+
170	120	700	8.2	3.6	1.1	152.4	0.7	149.3	135.2	4.1	4.3%	F*-NaCl +
207	72	550	8.5	9.6	2.1	102.8	2.2	256.7	60.4	2.0	-6.9%	F*-NaHCO3+
208	84	500	8.3	7.2	8.9	129.4	3.5	251.7	37.8	75.0	0.4%	F0-NaHCO3+
209	87	500	8.8	5.3	5.6	102.4	2.8	237.5	37.8	5.6	1.7%	F*-NaHCO3+
210	132	550	8.4	9.6	7.4	158.6	4.1	270.9	41.6	115.0	0.5%	F0-NaHCO3+
211	78	480	8.3	9.6	4.8	153.8	4.7	261.0	24.5	130.0	0.1%	F*-NaHCO3+
212	84	480	8.2	4.3	7.5	144.0	4.7	275.3	20.8	100.0	0.2%	F*-NaHCO3+

Section Subang I

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
250	48	560	8.1	5.2	8.7	118.1	3.5	320.3	13.2	9.8	3.1%	F*-NaHCO3+
263	1	8700	7.0	250.4	201.6	1224.8	46.7	501.5	2316.2	343.9	1.7%	B4-NaCl 0
265	1	1100	7.1	110.2	94.7	78.0	39.3	614.3	83.9	123.0	8.2%	F3-MgHCO3+
268	1	1450	7.4	91.7	57.2	148.4	24.9	614.3	140.3	94.5	1.2%	F3-MgHCO3+
273	45	1500	7.6	47.6	65.5	146.6	4.9	170.2	380.6	9.8	1.9%	b2-MgCl 0
277	36	2900	7.4	229.5	81.1	225.0	13.7	300.9	716.8	119.2	1.1%	b4-CaCl -
283	36	330	8.2	7.8	8.6	62.3	3.0	225.7	13.2	6.9	-4.1%	F0-NaHCO3+
332	36	380	7.7	10.4	5.6	76.3	4.0	242.8	13.2	18.4	-3.7%	F*-NaHCO3+
337	1	2400	7.0	59.0	64.5	221.8	3.5	772.3	76.8	110.6	2.4%	F3-NaHCO3+
340	2	2750	7.0	230.3	196.1	340.7	6.0	626.9	764.7	300.7	5.6%	b4-MgCl +
343	33	1300	6.9	84.7	95.3	82.4	5.0	441.6	34.5	300.7	4.3%	F3-MgHCO3+
351	2	3100	6.4	417.9	129.9	292.3	6.9	291.6	900.0	637.6	1.1%	b4-CaCl 0
354	8	290	6.1	24.4	8.4	57.6	2.9	200.5	21.5	39.4	-2.4%	F0-NaHCO3+
356	12	200	6.0	19.8	15.6	36.6	2.6	178.2	10.7	12.3	6.1%	F1-MgHCO3+
357	1.5	140	5.5	4.0	6.6	27.5	4.5	44.6	37.6	9.8	1.4%	F*-NaCl +
359	12	360	6.5	15.2	11.8	74.5	0.7	289.6	10.7	8.4	-2.3%	F0-NaHCO3+
360	18	400	6.6	32.0	16.6	65.5	4.5	323.0	10.7	17.2	-0.2%	F1-NaHCO3+

361	18	360	6.4	19.8	12.2	61.9	1.8	278.5	10.7	8.9	-3.3%	F0-NaHCO3+
368	28	250	5.9	19.8	14.0	37.8	3.6	178.2	9.4	14.8	5.2%	F1-MgHCO3+
371	2	140	6.0	3.8	5.1	35.5	0.1	89.1	14.8	9.8	1.7%	F*-NaHCO3+
372	2	39	5.0	1.4	6.9	6.7	1.2	26.7	13.4	9.8	-3.0%	F*-MgMix +
375	1.1	530	6.6	36.6	18.0	81.1	0.3	378.7	16.1	39.4	-4.5%	F1-NaHCO3+
379	12	390	6.0	35.1	18.8	48.6	4.5	222.8	24.2	19.7	7.6%	F1-CaHCO3+
382	24	380	6.5	36.6	15.7	47.4	5.9	345.3	12.4	14.8	-8.5%	F1-CaHCO3+
384	24	420	7.5	39.0	30.3	76.3	5.0	523.5	9.4	4.9	-6.3%	F2-MgHCO3+
385	14	450	6.8	119.8	48.7	122.3	4.3	189.4	16.1	536.3	2.3%	F3-CaSO4 +
386	8	1500	6.9	184.4	69.7	168.7	6.9	512.4	21.5	629.8	0.7%	F3-CaSO4 +
388	2	1600	6.9	170.7	72.6	194.2	4.8	534.7	21.5	612.5	2.1%	F3-CaSO4 +
392	12	1800	7.4	224.0	100.8	166.1	6.1	534.7	18.8	647.0	8.2%	F4-CaSO4 +
394	10	850	6.7	51.3	97.8	46.5	2.4	512.2	38.9	113.2	3.4%	F3-MgHCO3+
396	20	1000	6.9	96.0	41.3	191.7	4.5	601.5	22.8	182.0	7.6%	F3-NaHCO3+
398	21	300	7.9	10.4	14.1	76.3	4.7	245.1	10.7	53.1	-2.9%	F0-NaHCO3+
401	5	870	7.6	45.7	14.5	163.5	26.4	311.9	80.5	172.2	1.3%	F1-NaMix +
402	20	210	8.0	5.2	4.1	64.9	0.1	155.9	10.7	9.8	5.6%	F*-NaHCO3+
404	12	500	7.0	24.4	6.8	86.5	0.7	200.5	26.8	103.3	-5.4%	F0-NaHCO3+
433	3.5	360	6.6	12.2	8.9	59.4	0.3	200.5	13.4	4.9	2.2%	F0-NaHCO3+
437	11	340	6.3	32.0	15.1	42.6	2.0	211.6	26.8	13.8	2.5%	F1-CaHCO3+
443	12	83	5.3	5.2	8.5	6.4	0.6	22.3	16.1	19.7	0.9%	F*-MgMix +
452	12	100	5.6	3.0	7.6	3.0	0.2	33.4	10.7	4.9	-2.2%	F*-MgHCO3+
452	5	70	5.0	3.0	5.3	3.4	0.4	11.1	18.8	4.9	-4.5%	F*-MgCl 0
453	18	115	6.0	16.8	8.9	7.7	0.8	89.1	8.1	14.8	-1.7%	F0-CaHCO3+
456	4	78	5.9	3.9	10.8	4.9	1.1	44.6	16.1	4.9	1.5%	F0-MgHCO3+

Section Subang II

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
166	24	1700	6.9	154.8	53.0	115.9	1.6	557.7	182.5	109.4	1.8%	f3-CaHCO3+
168	32	290	7.5	1.2	5.2	65.0	0.9	193.4	20.3	5.8	-7.3%	F*-NaHCO3+
169	3	1500	7.6	82.9	31.2	137.1	4.7	289.7	218.0	69.1	1.8%	f2-CaMix +
170	144	630	8.0	1.3	6.6	130.0	1.5	265.9	55.5	34.6	-2.6%	F*-NaHCO3+
172	132	550	8.0	1.2	3.7	115.0	1.1	217.2	41.2	43.2	-2.1%	F*-NaHCO3+
173	28	2800	7.5	172.4	53.1	290.4	8.5	120.8	761.9	83.5	1.2%	b3-CaCl -
175	168	650	8.0	1.2	6.6	120.0	1.7	266.0	52.6	49.0	-7.8%	F*-NaHCO3+
178	105	720	8.0	1.2	6.6	145.0	2.4	314.1	46.9	8.6	2.4%	F*-NaHCO3+
180	66	750	8.0	5.0	5.8	150.0	3.5	458.7	13.2	8.6	-4.7%	F*-NaHCO3+
183	42	1700	8.0	32.5	20.3	290.0	7.0	337.9	317.1	14.4	4.2%	b1-NaCl +
185	96	760	8.0	1.3	6.6	150.0	2.0	337.9	62.6	20.2	-3.6%	F*-NaHCO3+
191	132	570	8.0	1.3	2.2	115.0	1.1	193.4	48.3	49.0	-2.5%	F*-NaHCO3+
192	60	810	8.0	10.0	10.2	190.0	4.4	483.1	48.3	11.5	1.0%	F0-NaHCO3+
197	39	390	8.3	4.9	25.9	44.0	0.9	170.2	41.3	6.9	2.5%	F1-MgHCO3+
199	48	650	7.9	18.2	12.7	109.3	2.5	170.2	112.0	4.0	5.8%	F0-NaCl +
201	114	660	8.2	5.2	8.7	148.8	2.5	315.4	55.5	9.8	4.0%	F*-NaHCO3+
204	60	1350	7.3	167.1	73.1	340.1	4.0	352.0	705.5	136.5	1.3%	b3-NaCl 0
205	141	650	8.6	1.3	6.6	131.3	1.5	242.8	55.5	34.0	0.8%	F*-NaHCO3+
212	144	620	9.2	1.0	3.0	111.5	1.0	145.8	83.9	34.6	-2.9%	F*-NaMix +
215	48	1100	7.9	20.8	6.7	231.8	7.0	522.2	86.7	30.0	0.9%	F0-NaHCO3+
217	144	1050	8.5	2.6	5.8	187.8	2.5	170.2	191.1	35.7	-0.5%	f*-NaCl +
222	102	880	8.2	5.2	10.2	183.7	4.0	388.6	75.3	4.0	3.5%	F0-NaHCO3+
230	102	1150	8.3	10.4	5.6	214.2	3.0	230.6	236.5	5.2	-0.9%	f*-NaCl +
236	66	2900	7.5	148.1	51.3	426.8	20.5	206.2	764.7	11.5	9.9%	b3-NaCl 0
238	72	590	8.2	5.2	10.2	122.5	4.0	315.4	38.4	4.0	1.5%	F0-NaHCO3+
241	24	380	8.1	2.6	14.7	67.8	1.5	175.1	41.3	6.9	1.7%	F0-NaHCO3+
292	3	820	4.6	45.5	20.7	79.0	2.5	75.2	210.9	6.9	1.0%	f1-CaCl 0
293	12	590	6.3	59.2	22.5	37.6	0.1	225.7	83.9	9.8	1.3%	F2-CaHCO30
295	3	590	5.5	22.1	23.2	35.6	4.6	50.2	126.1	4.0	2.3%	F1-MgCl 0
297	3	1850	4.6	110.6	45.0	189.5	0.5	75.2	479.3	110.6	1.2%	b3-CaCl 0
298	2	2600	5.4	231.3	121.0	229.0	2.5	275.8	744.9	55.9	8.3%	b4-CaCl 0
315	24	470	8.3	20.8	17.1	104.9	1.5	200.6	107.6	35.7	-0.1%	F1-NaMix +
316	72	610	8.0	1.3	9.6	137.9	3.0	388.6	13.2	12.7	-0.5%	F*-NaHCO3+
317	24	4200	7.0	264.0	132.7	464.8	0.7	522.2	931.6	364.0	2.2%	b4-CaCl 0
318	36	390	8.6	7.8	8.6	78.8	1.5	211.1	59.7	12.7	-8.5%	F0-NaHCO3+
323	30	340	8.6	1.3	5.1	64.5	1.5	184.2	20.3	6.9	-5.8%	F*-NaHCO3+
330	20	780	7.9	15.6	5.4	55.7	1.5	180.0	13.2	9.8	2.2%	F0-NaHCO3+
410	4.5	720	7.0	86.9	25.3	64.3	55.8	412.1	77.8	103.3	-2.1%	F2-CaHCO3+

411	12	390	6.5	59.4	14.0	34.1	1.0	222.8	34.2	17.2	6.1%	F2-CaHCO3+
413A	2.5	2050	6.7	125.0	37.1	426.7	2.0	456.7	327.5	433.0	4.0%	b3-NaMix +
413B	5	780	6.2	30.0	11.4	206.5	0.8	133.7	209.4	128.9	2.9%	f1-NaCl +
415	3.5	80	5.5	3.0	2.2	23.3	0.0	22.3	18.8	14.8	5.5%	F*-NaMix +
525	5	230	6.1	18.6	4.0	15.5	3.2	73.5	17.5	12.3	1.5%	F0-CaHCO3+
528	10	90	5.3	6.8	3.2	1.6	0.1	22.3	9.7	1.0	1.6%	F*-CaHCO3 0
529	10	28	5.6	2.6	7.2	0.9	2.6	22.3	12.7	1.0	5.3%	F*-MgMix 0
530	10	45	5.7	7.8	4.0	3.4	0.6	37.9	8.8	1.0	-0.5%	F*-CaHCO3 0
531	8	27	5.3	5.2	8.5	1.4	0.1	29.0	12.7	1.0	8.9%	F*-MgHCO3 0

Section Subang III

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
1	120	750	7.5	8.8	2.1	306.8	4.6	241.6	112	375.8	-3.0%	F*-NaMix +
2	108	1200	7.7	13.1	3.9	342.0	4.6	181.2	239.2	334.1	-2.2%	f*-NaMix +
4	72	6500	7.4	468.6	252.8	1160.0	25.0	410.5	2683.5	138.2	5.5%	B5-NaCl -
5	108	1200	8.0	13.7	3.8	200.0	3.0	187.3	260.4	60.7	-8.9%	f*-NaCl 0
6	108	1100	6.9	8.5	0.9	200.0	2.6	199.5	189.7	58.6	-3.0%	f*-NaCl +
7	57	1200	7.7	16.5	5.1	240.0	6.3	471	154.4	2.8	-1.2%	f0-NaHCO3+
8	72	950	7.9	5.5	3.3	180.0	2.8	193.4	140.3	107.4	-5.1%	F*-NaMix +
9	72	1050	7.5	9.5	1.2	190.0	3.5	229.3	112	25.8	9.0%	F*-NaHCO3+
11	78	1100	7.8	12.5	1.5	230.0	4.4	217.2	239.2	44.6	-1.7%	f*-NaCl +
13	54	1250	7.5	9.5	2.1	240.0	1.2	181.2	253.3	51.6	-0.3%	f*-NaCl +
14	96	5000	7.3	79.2	12.5	800.0	10.5	72.6	1327.1	23.7	1.2%	B2-NaCl 0
16	96	1800	7.5	23.2	14.6	660.0	10.4	314.5	832	80.9	1.7%	b1-NaCl +
17	96	1050	8.0	6.8	2.0	200.0	3.5	217.2	96.8	72.5	8.7%	F*-NaMix +
31	122	750	8.0	8.9	8.2	249.2	3.4	241.6	210.9	139.5	-3.1%	f0-NaMix +
32	120	670	8.3	7.5	0.7	130.0	1.4	229.4	83.8	55.1	-8.6%	F*-NaHCO3+
37	18	3000	7.1	59.0	54.3	464.4	14.1	447.1	663.1	65.6	1.0%	b2-NaCl +
47	96	2950	7.2	93.7	58.7	510.0	22.0	344	762	41.1	7.1%	b3-NaCl +
49	54	1650	7.5	23.7	19.6	345.0	9.5	483.1	281.6	13.2	5.6%	f1-NaMix +
51	160	620	8.3	3.7	0.8	130.0	1.3	217.2	55.5	71.1	-5.3%	F*-NaHCO3+
54	90	1150	8.1	75.5	41.2	187.8	3.4	199.5	338.1	108.8	1.1%	b2-NaCl 0
56	36	6200	7.1	353.7	190.7	603.8	18.9	193.4	1850	139	1.5%	B5-CaCl -
59	126	690	8.5	7.5	5.7	160.0	1.1	223.3	97.9	57.2	1.4%	F*-NaMix +
138	72	580	7.9	1.2	9.6	130.0	2.2	314.1	27.4	28.8	0.3%	F*-NaHCO3+
141	117	650	8.2	2.5	7.3	140.0	1.7	337.9	27.4	25.9	0.1%	F*-NaHCO3+
144	12	1950	6.7	223.1	90.1	167.3	0.2	507.5	336.2	357.1	1.2%	b4-CaMix +
460	108	600	8.5	5.2	1.4	132.8	1.5	267.3	25.3	44.3	1.4%	F*-NaHCO3+
464	4	1850	7.1	76.2	36.6	298.2	3.6	556.9	160.5	188	6.2%	f2-NaHCO3+
467	69	715	8.0	6.1	3.6	161.0	3.6	423.3	38.9	1	-2.3%	F*-NaHCO3+
468	126	555	8.6	3.0	1.4	130.3	1.2	278.5	37	36.9	-3.3%	F*-NaHCO3+
469	128	550	8.4	1.5	0.7	130.3	1.2	256.2	23.3	39.4	1.3%	F*-NaHCO3+
470	102	645	8.1	3.0	0.6	148.2	2.3	334.2	33.1	29.5	-2.3%	F*-NaHCO3+
471	28	1530	6.7	85.3	22.9	241.5	4.2	378.7	126.5	201.7	9.0%	F2-NaMix +
474	2	875	6.4	70.1	19.9	64.9	38.2	334.2	62.3	39.4	5.2%	F2-CaHCO3+
475	2	1230	6.0	91.4	35.3	112.4	8.0	271.8	167.3	78.7	7.5%	f2-CaMix +
476	3	3440	6.3	211.8	81.1	383.4	6.6	140.4	482.5	632.2	7.9%	b4-CaMix +
477	2	1640	6.3	153.9	60.8	84.5	8.0	389.9	220.8	130.4	3.8%	f3-CaMix +
479	150	615	8.0	6.1	3.9	145.6	2.1	356.4	26.3	8.4	1.8%	F*-NaHCO3+
480	2	1890	5.6	112.8	31.3	191.7	6.4	89.1	348.2	179.6	5.3%	b3-NaCl 0
483	24	3130	6.3	246.9	54.1	373.1	0.8	345.3	315.2	696.7	6.4%	b4-CaMix +
485	72	470	7.8	21.2	9.0	116.5	4.9	367.6	24.3	24.6	-1.7%	F0-NaHCO3+
488	2	4150	6.5	188.9	59.2	353.0	24.1	345.3	489.3	464.9	1.9%	b3-NaMix +
489	144	440	8.0	13.0	11.1	84.7	1.0	245.1	31.1	14.8	0.7%	F0-NaHCO3+
496	24	660	6.7	71.2	22.3	21.5	0.1	300.7	37	24.6	-1.2%	F2-CaHCO3+
497	2	1150	7.2	33.5	11.9	199.4	0.8	445.5	72	68.9	2.6%	F1-NaHCO3+
498	8	440	6.2	24.4	7.6	69.1	0.4	233.9	15.6	27.1	0.2%	F0-NaHCO3+
504	24	375	6.4	16.8	7.9	66.7	1.2	189.4	23.3	9.8	5.4%	F0-NaHCO3+
505	3	1870	6.5	202.7	30.9	141.7	8.0	345.3	254.9	142.7	9.2%	f3-CaMix 0
509	2	535	7.5	25.7	19.5	24.4	5.5	200.5	21.4	17.2	-1.9%	F1-MgHCO3+
511	40	650	5.9	57.9	17.9	63.1	0.7	115.8	59.3	142.7	4.3%	F2-CaMix +
512	18	1020	6.1	135.4	37.0	34.1	1.8	174.8	26.3	344.4	2.5%	F3-CaSO4 +

Section Subang IV

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
60	2	1350	6.8	137.5	65.3	160.0	13.0	380.6	126.2	301.3	9.7%	F3-CaMix +
62	144	9000	6.8	160.5	35.1	1956.1	15.3	314.0	2499.8	885.1	1.2%	B3-NaCl +
63	96	1100	8.0	8.7	3.0	250.0	4.0	302.0	140.3	76.0	5.3%	F*-NaMix +
67	96	2100	7.6	12.5	7.5	420.0	4.5	169.0	465.3	92.1	4.8%	b0-NaCl +
70	108	3600	7.2	100.8	57.7	538.0	18.7	434.9	832.6	110.2	1.1%	b3-NaCl +
71	2	2900	6.7	179.2	103.0	132.4	3.7	401.2	521.8	57.6	1.7%	b4-CaCl 0
74	128	920	8.1	7.5	2.2	200.0	2.0	241.6	112.0	72.5	3.8%	F*-NaMix +
77	126	2900	7.5	23.4	4.7	529.1	4.5	120.8	719.6	83.7	1.4%	b0-NaCl 0
84	120	2900	7.3	19.9	6.5	490.9	4.7	133.0	634.8	101.8	1.8%	b0-NaCl +
89	78	1900	7.8	14.1	9.0	614.3	7.4	241.6	832.6	80.9	-1.4%	b0-NaCl 0
93	80	3900	7.6	29.8	12.5	511.8	8.7	156.8	725.2	64.2	1.3%	b1-NaCl 0
94	96	1300	7.9	13.4	10.3	581.0	8.5	241.6	846.7	72.5	-4.2%	b0-NaCl 0
95	66	4900	7.2	141.7	104.2	549.4	22.9	289.7	1200.0	16.7	1.5%	B3-NaCl 0
101	138	3250	7.7	28.7	11.0	520.0	6.5	139.1	945.6	47.4	-8.8%	b1-NaCl -
106	114	590	8.4	2.7	6.2	130.0	3.2	308.1	27.3	48.1	-3.3%	F*-NaHCO3+
108	60	800	7.7	12.5	3.0	160.0	3.8	447.1	44.2	0.7	-4.0%	F*-NaHCO3+
109	1	1100	6.4	110.2	62.2	61.1	27.5	314.2	66.8	313.8	1.5%	F3-CaMix +
110	1	1000	6.5	110.1	2.6	112.2	9.4	350.1	83.8	152.0	-2.0%	F2-CaHCO3+
113	156	780	8.7	6.3	4.2	140.0	1.1	205.6	72.5	133.2	-9.4%	F*-NaMix +
115	114	650	8.2	3.8	3.0	140.0	1.1	314.2	38.6	39.7	-3.7%	F*-NaHCO3+
118	135	650	8.1	2.5	2.4	130.0	1.9	301.9	27.3	37.7	-3.8%	F*-NaHCO3+
119	132	660	8.8	2.5	2.9	130.0	1.3	289.7	20.3	51.8	-2.8%	F*-NaHCO3+
120	4	3000	7.0	297.8	143.2	244.5	3.0	700.3	716.8	218.9	1.5%	b4-CaCl 0
122	54	1750	7.6	128.9	70.7	145.3	4.3	434.9	182.5	276.5	1.8%	f3-CaMix +
125	21	3500	7.0	327.4	187.9	120.0	15.0	652.1	761.3	253.4	-0.1%	b4-CaCl 0
126	6	2100	7.0	125.5	92.1	120.0	14.0	652.1	161.6	175.7	1.3%	f3-MgHCO3+
128	18	850	7.3	32.5	89.3	90.0	2.2	603.9	13.2	141.1	-1.0%	F3-MgHCO3+
129	12	2100	7.4	154.4	92.7	157.7	2.0	628.3	218.0	230.4	2.3%	f3-CaMix +
131	4	450	6.5	38.6	31.3	13.4	2.6	169.0	59.7	23.0	2.2%	F2-MgHCO3+
132	15	340	7.1	45.0	32.1	25.0	0.6	362.3	13.2	14.4	-4.9%	F2-MgHCO3+
136	9	1550	7.0	118.8	64.1	129.1	2.7	557.7	92.4	213.1	2.1%	F3-CaHCO3+
137	90	690	8.0	2.5	8.8	145.0	2.6	410.5	27.4	11.5	-3.5%	F*-NaHCO3+
148	42	1400	7.4	35.0	39.6	250.0	10.0	410.5	210.9	49.0	8.2%	f2-NaMix +
151	120	1100	8.0	2.5	10.3	250.0	4.4	483.1	98.0	5.8	5.1%	F*-NaHCO3+
155	120	760	8.5	1.2	6.6	165.0	2.0	337.9	41.2	66.2	-1.6%	F*-NaHCO3+
161	42	5600	7.6	155.4	134.2	696.4	27.4	266.0	1478.3	129.6	1.0%	B4-NaCl 0
162	60	9900	7.1	390.8	331.9	1024.1	39.7	193.4	2956.2	167.0	1.3%	B5-MgCl -
163	48	5200	7.4	153.9	143.0	690.0	27.1	289.7	1475.5	129.6	1.1%	B4-NaCl 0
164	102	3400	7.8	32.5	18.8	677.6	6.8	169.0	846.7	40.3	8.8%	b1-NaCl +

Section Indramayu I

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
34	0	1350	8.4	24.9	12.5	162.5	1.4	194.1	240.8	58.6	-8.8%	f1-NaCl 0
35	180	1550	8.5	12.5	0.1	263.4	2.2	238.9	263.3	50.8	-1.0%	f*-NaCl +
36*	146	1800	?	17.4	3.4	290.0	4.9	254.2	330.2	157.6	-9.4%	b0-NaCl +
36**	146	?	?	11.8	1.2	352.8	5.1	200.5	346.9	149.0	-0.0%	b*-NaCl +
***	144	?	?	3.1	0.0	196.7	2.6	176.6	138.4	76.6	2.2%	F*-NaMix +

* Pre-war deep well Patrol in September '80
** Pre-war deep well Patrol in 1938
*** Pre-war deep well Anjatan in 1938

Section Indramayu II

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
161	96	6800	?	65.1	67.4	1100.0	21.5	532.5	1462.3	1.0	6.7%	B3-NaCl +

Section Indramayu III

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
142	80	7000	?	78.1	44.3	1180.0	16.3	532.5	2087.9	23.5	-6.9%	B2-NaCl -
159	84	3700	?	34.7	23.6	570.0	11.8	459.9	691.6	2.4	3.0%	b1-NaCl +

Shallow wells in the Cimanuk delta

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
7	3.7	3360	7.8	86.3	92.2	577.5	45.6	599.0	959.9	282.0	-5.7%	b3-NaCl +
9	0.3	1539	7.3	24.1	67.0	237.5	9.6	713.5	167.2	136.0	-5.3%	f2-NaHCO3+
9	0.3	1210	7.4	72.2	74.6	125.0	18.5	550.6	135.7	117.0	1.2%	F3-MgHCO3+
12	0.4	3220	7.6	68.2	110.6	547.5	25.5	921.4	659.1	285.0	-3.5%	b3-NaMix +
20	0.0	2300	8.0	106.9	93.7	285.5	83.2	676.0	376.1	215.0	2.6%	b3-NaMix +
28	0.3	2330	7.5	52.2	39.8	416.2	8.7	415.7	557.3	88.0	-0.3%	b2-NaCl +
30	0.7	6350	7.2	252.8	206.3	947.5	33.5	696.6	2204.9	293.0	-5.3%	B4-NaCl -
31	0.6	5306	7.2	140.5	102.5	1091.5	10.8	876.4	1623.2	540.0	-6.1%	B3-NaCl +
32	4.0	1132	7.9	93.9	57.7	96.3	3.0	479.0	111.0	122.0	0.6%	F3-MgHCO3+
33	3.9	776	7.9	64.8	38.0	66.3	6.1	390.0	57.0	70.9	-0.4%	F2-CaHCO3+
34	3.1	783	7.2	66.3	43.4	56.3	3.7	317.0	58.0	63.9	7.2%	F2-MgHCO3+
36	3.7	1232	7.9	76.9	52.4	129.0	6.4	545.0	162.0	68.9	-3.5%	f3-MgHCO3+
37	3.2	1144	7.9	61.7	50.4	132.0	5.1	479.0	127.0	95.9	-1.3%	F2-MgHCO3+
50	0.6	1946	7.5	80.3	58.0	405.0	16.2	758.4	261.7	340.0	-0.2%	f3-NaMix +
52	0.7	5550	7.3	92.3	68.0	944.0	45.5	960.7	1587.1	125.0	-9.3%	B3-NaCl 0
52	0.3	1942	7.5	36.1	21.7	405.0	16.2	747.2	285.9	97.0	-1.6%	f1-NaHCO3+
54	0.4	667	7.5	56.2	17.3	90.0	11.5	398.9	29.1	74.0	-2.7%	F2-CaHCO3+
56	0.3	1780	7.6	100.3	71.0	205.0	19.0	618.0	271.4	210.0	-4.5%	f3-MgMix +
57	0.8	3470	7.3	256.8	45.3	667.5	16.2	241.6	1051.6	221.0	9.2%	B4-NaCl 0
62	0.7	3080	7.3	140.5	72.3	479.4	5.7	561.8	688.1	484.0	-6.5%	b3-NaCl +
63	1.3	5370	7.4	305.0	67.4	820.0	25.7	651.7	1417.5	486.0	-3.1%	B4-NaCl 0
66	0.9	4470	7.5	192.6	88.7	845.0	16.8	443.8	1126.7	656.0	1.3%	B4-NaCl +
68	0.8	1770	7.3	152.5	34.8	232.5	11.8	567.4	181.7	371.0	-2.9%	f3-CaMix +
69	5.1	1299	7.9	71.8	34.6	202.0	11.6	576.9	125.0	110.0	0.8%	F2-NaHCO3+
70	4.0	1299	8.0	83.0	42.0	172.0	15.0	581.9	108.0	164.0	-1.7%	F2-NaHCO3+
71	3.9	2220	7.9	116.8	60.9	300.0	56.8	660.2	363.0	226.0	-0.8%	b3-NaMix +
72	4.1	1350	8.1	62.6	30.8	205.0	20.5	547.0	136.0	118.0	-0.5%	F2-NaHCO3+
73	6.0	5530	7.9	209.8	120.5	1012.0	23.1	749.2	1478.9	563.0	-0.6%	B4-NaCl +
74	5.7	4810	7.9	220.1	164.5	732.0	79.1	862.1	1193.9	574.0	-1.2%	B4-NaCl +
76	3.7	877	7.7	68.9	43.4	72.3	10.1	380.0	48.5	102.0	3.4%	F2-MgHCO3+
95	4.7	1700	7.5	134.3	62.2	175.0	14.3	491.0	231.0	293.0	-2.1%	f3-CaMix +
97	4.4	1010	7.9	64.6	51.5	83.0	12.9	434.0	73.0	150.0	-3.8%	F2-MgHCO3+
97	3.6	1490	7.8	82.6	69.6	172.0	18.8	532.0	198.0	163.0	0.3%	f3-MgMix +
99	4.0	4240	7.7	311.8	150.1	534.0	39.4	514.9	1019.9	656.0	1.2%	B4-CaCl +
101	0.9	2260	7.3	112.4	30.1	375.0	11.7	674.2	402.2	193.0	-3.4%	b3-NaMix +
102	0.0	7260	7.3	32.1	28.6	1548.8	7.3	370.8	2495.7	10.0	-3.5%	B1-NaCl 0
104	0.7	3900	7.0	148.5	19.4	855.5	8.7	915.7	940.1	148.0	2.0%	b3-NaCl +
115	6.1	800	7.9	32.5	21.8	116.0	9.2	455.0	14.5	72.2	-3.7%	F1-NaHCO3+
117	2.7	1084	7.9	81.8	58.4	93.6	12.7	407.0	86.5	180.0	1.6%	F3-MgHCO3+
128	3.2	5220	7.8	247.5	197.6	863.9	35.5	926.8	1164.8	1050.0	-2.1%	B4-NaMix +
131	1.2	17650	7.8	135.5	366.6	3892.0	153.0	685.8	6543.8	757.0	-0.3%	B5-NaCl 0
132	1.4	10560	7.9	134.1	346.7	2090.8	104.6	540.0	3793.0	522.0	0.8%	B5-NaCl +
134	1.9	22200	7.7	323.8	1026.0	4264.4	462.3	813.9	8897.6	1299.7	1.1%	B6-NaCl +
142	0.8	1851	7.5	64.2	90.6	227.5	11.1	707.9	273.8	247.0	-8.0%	f3-MgMix +
149	0.4	2610	7.9	52.2	48.8	582.5	25.5	589.9	523.4	185.0	7.1%	b2-NaCl +
150	1.1	6850	7.3	196.6	162.2	1209.5	137.0	882.0	2362.4	201.0	-3.7%	B4-NaCl 0
151	0.8	7750	7.3	240.8	402.5	958.8	43.0	988.8	2665.3	540.0	-7.7%	B5-MgCl 0
153	2.0	10360	7.7	297.8	542.7	1614.5	157.3	693.7	3902.9	317.0	2.2%	B5-NaCl 0
154	1.5	4000	8.0	48.9	81.2	758.9	44.4	779.1	963.8	213.0	-1.3%	b3-NaCl +
155	1.8	13220	7.7	310.1	490.2	2277.9	152.1	621.1	4750.1	716.0	-0.1%	B5-NaCl 0
176	0.5	5350	7.3	204.7	37.8	1062.0	16.2	691.0	1550.7	494.0	-4.3%	B3-NaCl 0
177	1.4	2230	7.6	128.4	60.6	297.5	7.6	471.9	450.7	239.0	-1.8%	b3-NaCl +
178	1.8	7080	7.2	333.1	68.3	1298.0	5.5	567.4	2264.9	988.0	-8.6%	B4-NaCl 0
179	2.2	7340	7.4	345.1	90.0	1327.5	6.8	404.5	2507.8	772.0	-6.2%	B4-NaCl -
196	5.4	10010	7.3	349.9	176.8	2170.8	11.6	594.9	3519.7	1469.7	-4.8%	B5-NaCl 0
199	72.0	5840	7.8	56.9	32.0	1271.0	18.7	508.0	1869.9	32.4	-0.4%	B2-NaCl 0

201	3.7	1678	7.7	127.4	58.6	188.0	11.3	323.0	311.0	251.0	0.9%	b3-CaMix +
203	1.4	5020	7.3	217.8	71.4	846.5	3.2	561.8	1478.0	72.6	1.2%	B4-NaCl 0
207	0.5	2140	7.5	116.4	64.3	377.0	19.0	466.3	382.8	602.0	-5.1%	b3-NaMix +
209	12.0	3990	7.4	124.4	69.7	845.0	13.2	691.0	964.4	502.0	0.1%	b3-NaCl +
210	8.0	2280	7.2	64.2	20.2	550.0	7.1	724.7	324.7	416.0	-1.2%	b2-NaMix +
220	3.2	4200	7.8	313.3	202.9	534.0	20.0	668.7	1074.8	823.0	-2.1%	B5-MgCl +
221	3.4	3090	7.9	211.4	150.8	392.9	26.7	532.0	612.9	716.0	-0.2%	b4-MgMix +
222	4.1	1670	7.8	98.9	53.2	208.0	22.1	359.0	232.0	289.0	1.3%	f3-NaMix +
223	6.0	1542	8.1	67.5	54.1	243.9	11.4	465.0	141.0	334.0	0.4%	F2-NaMix +
224	3.8	2960	7.6	261.4	132.7	231.0	97.8	496.9	645.9	564.0	-2.1%	b4-CaMix +
225	4.4	4580	7.5	424.4	302.7	412.0	30.2	359.0	1358.7	1129.7	-2.2%	B5-MgCl 0
226	4.0	6860	7.6	705.8	533.9	706.0	31.8	629.0	2173.7	1915.5	-0.4%	B6-MgCl +
232	6.6	7950	7.7	608.0	394.8	1131.0	48.1	721.8	2532.8	1830.0	-3.5%	B5-MgCl +
234	0.3	1970	7.5	168.5	89.9	192.5	18.5	646.1	290.8	370.0	-3.6%	f3-CaMix +
236	0.9	2506	7.4	144.5	62.1	450.0	11.2	657.3	397.4	494.0	-0.1%	b3-NaMix +
238	0.7	1240	7.5	76.2	50.0	131.0	2.6	533.7	111.5	202.0	-8.1%	F2-MgHCO3+
240	0.4	1384	7.5	114.4	61.3	142.5	14.5	359.6	147.8	309.0	2.4%	F3-CaMix +
254	3.1	1512	7.7	63.0	54.3	221.0	10.5	607.0	240.0	58.7	-1.3%	f2-NaHCO3+
257	4.2	1309	8.0	86.4	56.0	142.0	17.9	629.7	176.0	63.2	-3.3%	f3-MgHCO3+
261	14	1620	7.8	45.3	42.7	263.9	20.4	601.0	295.0	15.1	-2.0%	f2-NaHCO3+
262	3.3	3480	7.8	238.6	96.1	366.0	246.1	748.0	621.8	658.0	-1.7%	b4-NaMix +
264	1.6	3420	7.0	280.9	145.7	370.0	20.8	640.5	945.0	371.0	-2.6%	b4-CaCl 0
265	0.8	1121	7.9	64.2	32.5	215.0	12.5	539.3	99.3	127.0	4.2%	F2-NaHCO3+
267	0.5	1465	7.6	76.2	19.7	240.0	14.0	370.8	247.2	133.0	1.3%	f2-NaMix +
272	3.4	800	7.0	97.6	40.6	41.8	4.0	427.9	23.5	39.9	8.7%	F3-CaHCO3+
273	4.5	1204	7.9	119.7	50.7	103.0	10.4	589.9	49.5	199.0	-1.1%	F3-CaHCO3+
286	0	7370	7.3	342.1	220.2	1297.9	39.9	849.9	2212.7	793.0	-0.1%	B5-NaCl +

Section Cirebon I

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
9	3	2420	7.2	89.9	96.6	324.7	47.9	629.3	441.2	108.2	5.2%	b3-NaMix +
19	21	5500	7.0	77.5	51.7	1120.8	18.1	629.3	1378.8	295.2	1.8%	B3-NaCl +
27	21	6860	6.7	143.1	79.3	1305.8	16.8	717.7	1695.9	428.0	1.7%	B3-NaCl +
28	18	1444	7.3	23.9	13.0	350.9	6.9	530.0	193.0	93.5	4.8%	f1-NaHCO3+
30	12	3400	7.2	39.3	31.2	736.2	19.9	750.8	675.6	130.4	4.2%	b2-NaCl +
57	12	3720	6.7	189.8	87.7	132.3	4.8	541.0	220.6	334.6	1.1%	f4-CaMix +
58	12	1960	6.4	160.1	49.0	304.8	1.9	386.4	455.0	255.8	1.7%	b3-NaCl +
60	12	1270	6.5	67.4	20.6	213.7	1.1	375.4	96.5	206.6	4.4%	F2-NaMix +
282	4	1090	8.0	42.7	26.8	145.3	2.4	258.2	125.1	131.2	1.1%	F2-NaMix +
310	12	2880	7.3	162.5	55.4	287.9	3.6	850.0	235.0	194.3	1.4%	f3-CaHCO3+
313	12	2310	8.2	57.1	66.0	333.3	10.9	528.1	202.8	217.7	9.9%	f3-NaMix +
314	9	563	7.7	33.2	31.9	48.9	7.5	310.0	49.3	27.9	-3.3%	F2-MgHCO3+
317	18	3710	7.8	116.8	85.1	347.2	5.4	821.6	390.5	108.9	2.4%	b3-NaHCO3+
319	9	1190	7.8	75.2	64.3	104.8	6.5	598.6	125.1	5.6	1.1%	F3-MgHCO3+
320	5	486	7.8	22.3	39.1	45.9	7.2	316.9	20.9	27.9	1.1%	F2-MgHCO3+
323	8	837	7.7	97.9	13.4	53.4	21.8	422.5	66.3	16.8	-1.5%	F2-CaHCO3+
397	32	3950	7.1	184.6	153.9	270.9	18.0	469.5	729.1	228.9	1.6%	b4-MgCl 0
405	2.5	326	7.0	33.2	22.8	12.5	13.8	187.8	23.4	38.0	-1.1%	F1-MgHCO3+

Section Cirebon II

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
35	10	1760	7.0	78.6	66.7	162.4	49.9	397.5	317.1	73.8	2.2%	b3-MgCl +
79	17	444	7.2	29.0	22.9	40.1	1.7	303.9	16.6	2.5	-3.6%	F1-MgHCO3+
80	8	740	7.1	36.9	41.1	25.7	13.9	278.6	52.6	24.6	1.0%	F2-MgHCO3+
82	9	903	6.7	31.5	15.5	24.0	7.5	182.4	24.4	12.3	1.9%	F1-CaHCO3+
83	8.5	516	6.7	31.5	15.5	24.0	7.5	182.4	24.4	12.3	1.9%	F1-CaHCO3+
84	8	363	6.8	21.7	12.3	22.3	5.7	159.6	8.9	12.3	1.3%	F1-CaHCO3+
86	12	278	6.8	27.2	15.8	21.0	2.6	152.0	40.8	2.5	-0.8%	F1-CaHCO3+
91	9	379	7.4	30.4	25.3	18.6	8.8	240.6	10.9	27.1	-1.9%	F1-MgHCO3+
94	8	806	7.4	58.0	55.5	36.0	9.8	418.0	44.3	2.5	6.4%	F2-MgHCO3+

96	3	597	7.1	100.0	49.4	88.9	19.7	488.8	90.4	46.7	7.6%	F3-CaHCO_3+
97	18	551	7.7	57.7	5.0	59.5	10.3	352.0	16.6	2.5	-1.2%	F1-CaHCO_3+
98	12	1018	7.2	96.0	2.2	109.3	15.2	501.5	57.2	27.1	-1.4%	F2-NaHCO_3+
107	9	846	7.1	80.3	45.1	37.3	13.2	455.9	48.0	9.8	3.5%	F2-CaHCO_3+
324	1	472	7.5	38.6	30.4	32.9	4.8	234.7	41.7	22.3	4.3%	F2-MgHCO_3+
325	6	228	7.0	18.5	18.3	9.6	5.0	140.8	15.2	16.8	-1.9%	F1-MgHCO_3+
327	1	188	6.9	14.3	21.4	7.2	4.1	140.8	9.5	11.2	1.6%	F1-MgHCO_3+
330	2	248	7.0	20.4	12.8	10.7	6.3	122.1	13.3	16.8	-0.5%	F1-MgHCO_3+
332	6	310	7.5	31.3	20.1	13.2	2.3	183.1	22.7	16.8	-1.8%	F1-MgHCO_3+
333	2	668	8.1	49.0	28.4	10.7	5.9	164.3	91.0	33.5	-4.9%	F2-CaMix 0
379	1	294	6.6	30.3	15.1	9.1	5.1	129.1	20.7	19.5	2.7%	F1-CaHCO_3+
380	0.5	762	7.1	58.5	20.3	48.9	48.4	223.0	19.0	180.7	0.0%	F2-CaMix +
381	1	582	7.1	46.2	22.7	37.4	8.0	211.3	55.2	41.9	0.9%	F2-CaHCO_3+
385	2	780	7.2	82.2	30.4	55.8	45.4	363.8	89.6	61.4	2.1%	F2-CaHCO_3+

Section Cirebon III

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
49	48	1890	7.1	38.4	19.4	372.6	5.6	552.1	275.8	123.0	1.2%	f1-NaMix +
187	126	729	7.7	63.7	17.2	77.5	16.5	379.9	18.9	89.3	-1.4%	F2-CaHCO_3+
188	36	591	7.3	71.7	32.2	34.8	3.6	341.9	26.5	44.7	3.6%	F2-CaHCO_3+
190	36	1116	7.8	69.0	41.5	153.8	13.5	501.5	56.9	184.2	0.8%	F2-NaHCO_3+
199	30	1415	7.5	24.3	54.9	279.2	12.6	536.9	144.0	170.2	5.2%	F2-NaHCO_3+
200	156	1139	8.0	20.0	10.3	178.1	2.3	211.3	66.3	195.4	1.3%	F0-NaMix +
201	69	937	8.1	24.8	13.6	161.9	10.4	387.5	37.9	178.6	-7.1%	F1-NaHCO_3+
202	42	1338	8.0	41.4	37.6	275.1	9.2	392.6	193.3	132.9	8.5%	f2-NaMix +
205	39	1200	7.5	35.9	22.7	263.0	10.7	417.9	155.4	100.5	7.1%	f1-NaHCO_3+
206	132	880	7.9	16.6	10.1	194.0	1.7	215.3	75.8	161.9	5.8%	F0-NaMix +
207	27	2310	7.2	88.3	58.7	436.7	14.2	823.1	417.0	217.7	-2.0%	b3-NaMix +
215	48	615	7.9	26.7	7.4	97.6	13.9	347.0	26.5	20.7	-2.4%	F0-NaHCO_3+
216	72	665	8.0	30.7	3.3	105.2	15.0	326.2	30.3	44.7	-2.7%	F0-NaHCO_3+
217	42	1402	7.6	44.2	13.5	287.3	10.4	385.0	271.1	33.5	4.6%	f1-NaCl +
218	72	632	7.8	19.8	7.5	126.2	11.3	324.2	30.3	72.6	-2.0%	F0-NaHCO_3+
219	24	2510	7.2	46.9	61.9	542.2	30.0	937.1	377.2	51.4	8.0%	b2-NaHCO_3+
220	3	2330	7.1	124.2	55.4	396.2	19.1	747.2	417.0	88.2	4.8%	b3-NaMix +
222	3	1521	7.0	104.4	43.5	220.8	5.7	607.9	204.7	100.5	1.9%	f3-NaHCO_3+
229	6	1636	6.9	173.9	94.0	88.6	12.8	729.4	170.6	163.6	1.0%	f4-CaHCO_3+
230	30	928	7.4	27.6	30.2	159.9	11.7	600.3	37.9	27.9	-1.6%	F1-NaHCO_3+
234	36	929	7.3	44.2	23.8	149.7	12.0	577.5	41.7	11.2	0.5%	F2-NaHCO_3+
238	100	971	7.6	24.8	14.8	178.1	6.7	334.3	30.3	290.3	-8.8%	F1-NaMix +
343	0.5	2400	7.4	262.5	69.9	163.0	10.9	469.5	489.0	132.9	3.9%	b4-CaCl 0
344	0.5	1120	7.3	150.3	36.6	115.3	39.1	457.7	197.1	149.1	1.1%	f3-CaMix +
346	36	815	7.5	47.6	20.3	123.3	8.2	516.4	26.5	19.5	0.0%	F2-NaHCO_3+
349	1	1492	7.1	91.0	83.1	81.0	18.2	352.1	276.7	55.8	2.1%	f3-MgCl +
350	9	1017	7.3	87.0	42.2	86.0	8.4	516.4	68.2	61.4	0.4%	F2-CaHCO_3+
353	18	744	7.4	59.8	36.6	49.5	5.4	410.8	39.8	36.3	-1.9%	F2-MgHCO_3+
356	36	1028	8.0	29.9	20.3	175.8	6.3	422.5	121.3	39.1	-0.9%	F1-NaHCO_3+
357	0.5	4850	7.2	323.7	179.5	403.4	48.4	704.2	1103.1	145.1	4.2%	B4-CaCl 0
359	0.5	892	7.3	118.3	5.7	43.8	9.6	316.9	73.9	55.8	0.5%	F2-Ca$HCO_3$0
361	24	1152	7.9	61.2	38.2	140.4	6.1	645.5	56.9	79.3	-5.2%	F2-NaHCO_3+
363	36	784	7.6	54.4	32.5	61.5	7.5	492.9	19.0	39.1	-6.6%	F2-CaHCO_3+
365	6	679	7.1	72.1	23.6	32.5	6.3	316.9	51.2	57.5	-4.8%	F2-CaHCO_3+
366	1	591	7.3	59.8	13.0	38.1	9.6	316.9	36.0	25.1	-6.1%	F2-CaHCO_3+
367	36	1079	7.6	72.1	35.7	97.9	7.3	622.0	19.8	67.0	-5.1%	F2-CaHCO_3+

Section Brebes/Tegal I

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
21	54	3730	6.8	95.7	57.3	610.0	12.4	625.8	855.0	55.5	1.1%	b3-NaCl +
22	72	932	6.9	40.3	24.1	54.4	4.1	286.1	75.0	20.5	-5.6%	F1-CaHCO_3+
42	90	946	7.5	50.2	18.3	70.9	3.5	345.2	80.0	16.7	-7.0%	F2-CaHCO_3+
43	69	919	7.5	26.2	13.9	120.0	3.7	386.0	72.9	11.8	-5.3%	F1-NaHCO_3+

44	3	4150	7.0	72.2	162.7	409.9	10.5	739.2	986.1	55.5	-7.9%	b4-NaCl 0
53	78	1124	7.3	18.2	3.8	229.0	1.6	330.5	159.2	28.6	3.3%	f0-NaHCO3+
54	5	4720	7.4	42.3	49.0	1030.0	7.0	943.5	993.7	154.2	4.5%	b2-NaCl +
55	78	1166	7.6	16.2	6.9	245.4	1.1	295.7	163.2	33.1	8.7%	f0-NaMix +
57	36	2190	7.1	80.7	25.5	278.3	2.3	400.0	477.7	16.2	-5.4%	b2-NaCl 0
58	10	2350	6.7	124.9	39.2	250.1	4.5	456.5	412.5	86.5	-1.1%	b3-NaCl 0
59	4	918	6.9	100.8	14.7	67.4	3.3	478.1	75.0	17.6	-5.4%	F2-CaHCO3+
61	39	2060	7.2	98.8	30.0	168.0	1.6	566.7	225.0	30.8	-4.9%	f2-CaHCO3+
62	57	930	7.4	70.8	37.9	95.4	1.8	566.7	65.0	2.3	-1.5%	F2-CaHCO3+
63	3	1891	6.9	153.2	9.2	229.0	5.9	682.1	189.9	112.7	-1.0%	f3-NaHCO3+
66	36	1265	7.4	88.0	52.5	132.7	5.3	625.8	165.0	3.5	-1.2%	f3-CaHCO3+
67	5	1912	6.9	108.8	45.9	198.4	2.0	475.4	230.2	131.5	2.5%	f3-CaMix +
68	102	757	7.6	24.9	23.8	179.6	1.4	589.3	130.3	3.5	-9.6%	F1-NaHCO3+
71	7	1163	6.9	44.5	30.4	112.6	1.0	329.4	88.3	25.2	6.8%	F2-NaHCO3+
72	12	1121	7.1	12.3	26.3	165.5	0.3	491.8	54.9	8.3	1.0%	F1-NaHCO3+
73	5	1175	7.1	62.5	37.1	179.6	0.4	570.7	78.7	25.2	7.3%	F2-NaHCO3+
74	36	5200	8.0	157.0	116.7	1003.9	7.8	307.0	1392.8	940.0	-2.1%	B4-NaCl +
74A	38	4590	7.6	78.2	59.6	868.8	5.5	290.0	1199.4	765.0	-7.7%	B3-NaCl +
75	27	1290	8.2	66.5	34.7	217.0	4.0	509.9	39.0	305.0	-0.3%	F2-NaHCO3+
77	12	699	6.9	57.7	36.6	43.3	0.4	380.5	28.8	22.1	1.8%	F2-MgHCO3+
78	10	940	7.1	56.4	40.9	132.6	0.7	566.1	40.3	22.1	4.8%	F2-MgHCO3+
79	9	763	6.9	47.8	32.0	30.6	1.4	440.8	13.4	1.9	-9.0%	F2-MgHCO3+
80	75	1698	7.3	34.3	12.7	283.0	2.6	300.0	385.2	18.6	-3.3%	b1-NaCl 0
81	72	1910	7.2	68.3	42.2	292.4	3.9	373.9	441.2	20.5	1.8%	b2-NaCl +
82	6	8980	7.0	118.9	179.4	1635.8	35.0	795.7	2781.7	146.3	-1.0%	B4-NaCl 0
83	66	1570	7.2	24.2	14.7	264.2	3.8	326.1	326.2	5.9	-2.3%	b1-NaCl +
87	5	2930	8.0	220.2	129.5	409.9	1.4	679.7	444.9	898.0	-3.5%	b4-CaMix +
88	54	1910	8.2	45.8	26.4	397.0	4.1	444.0	142.0	512.0	-0.3%	F2-NaMix +
97	102	2250	7.8	62.2	12.5	468.8	3.7	121.8	329.5	802.5	-6.4%	b2-NaSO4 +
194	69	539	7.9	22.1	8.9	100.0	2.0	337.1	26.6	9.8	-1.9%	F0-NaHCO3+
215	28	750	8.0	65.5	20.4	85.0	2.4	493.0	22.0	12.5	-1.4%	F2-CaHCO3+
218	120	29400	7.1	913.0	517.5	8250.0	2.1	33.7	15689	7.5	0.4%	S6-NaCl -
220	9	2830	8.1	62.6	34.7	577.0	2.2	677.9	399.9	472.0	-1.7%	b2-NaMix +
223	22	731	7.7	37.1	22.1	112.5	2.5	460.7	29.1	12.5	-0.0%	F1-NaHCO3+
451	6	757	7.1	41.2	19.5	105.9	1.2	403.7	44.1	12.7	1.0%	F1-NaHCO3+
452	9	2870	7.1	24.7	59.3	388.8	1.0	589.3	435.5	122.0	-3.0%	b2-NaCl +

Section Brebes/Tegal II

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Bal. Error	Hydrochemical Type
5	150	1115	7.4	10.8	8.0	236.0	8.4	595.7	72.0	23.1	-2.5%	F0-NaHCO3+
6	84	1106	8.2	20.2	7.5	215.0	4.2	625.8	70.0	26.9	-7.1%	F0-NaHCO3+
8	135	1090	8.1	30.2	7.5	268.8	4.3	640.6	65.0	23.6	4.1%	F1-NaHCO3+
9	132	1860	7.1	36.3	18.4	248.2	16.3	634.3	90.0	66.5	0.8%	F1-NaHCO3+
10	114	1290	7.4	14.5	8.9	259.5	6.5	507.5	156.0	29.7	-1.6%	f0-NaHCO3+
12	5	2340	7.0	92.1	63.9	264.2	48.8	611.3	440.0	7.3	0.0%	b3-NaCl +
14	108	1235	8.1	20.2	13.6	258.6	6.8	699.7	70.0	6.5	-0.1%	F1-NaHCO3+
16	5	7130	7.2	58.8	152.9	1458.2	116.2	758.6	2400.0	59.1	0.3%	B3-NaCl +
33	5	1530	6.7	67.3	42.7	187.3	7.3	539.2	190.0	21.0	1.9%	f2-NaHCO3+
34	4	543	6.6	43.9	19.6	50.2	1.6	260.9	39.0	4.9	4.8%	F1-CaHCO3+
36	17	590	6.7	44.9	27.7	24.5	1.1	308.7	18.0	4.9	-0.5%	F2-MgHCO3+
52	6	1930	6.8	56.6	58.1	167.9	2.5	513.1	298.0	48.5	-8.7%	f2-MgMix +
55	8	488	7.9	45.3	30.2	18.0	17.0	271.3	20.0	3.0	8.1%	F2-MgHCO3+
58	72	1422	7.3	12.2	8.4	299.5	3.2	578.7	92.8	62.8	3.6%	F0-NaHCO3+
59	72	1465	7.3	14.1	7.2	301.8	3.5	604.3	96.0	59.1	2.4%	F0-NaHCO3+
231	116	1300	7.8	20.2	15.2	292.0	2.7	581.2	155.0	33.2	1.5%	f1-NaHCO3+
235	192	2530	7.2	29.4	11.2	518.3	6.8	152.2	800.0	2.3	-0.0%	b1-NaCl 0
240	122	1042	7.8	20.2	12.0	239.1	8.3	625.8	55.0	14.4	2.0%	F0-NaHCO3+
248	86	980	7.4	11.7	6.7	219.6	1.6	530.5	48.0	6.5	2.6%	F0-NaHCO3+
249	3.9	8840	7.0	124.9	162.9	1607.3	25.0	1043.5	2550.0	55.5	-0.0%	B4-NaCl +
250	4	10240	7.6	105.8	166.6	2660.0	40.0	1394.0	3750.0	48.5	2.3%	B4-NaCl +
256	4	3040	6.9	82.2	66.1	330.0	9.6	747.8	470.0	59.1	-5.1%	b3-NaMix +
258	112	975	7.4	12.1	17.3	229.0	1.8	543.5	68.0	11.0	4.2%	F1-NaHCO3+
276	130	1850	7.3	30.2	30.3	370.0	4.5	478.1	375.0	25.3	3.2%	b1-NaCl +
281	54	1632	7.2	33.0	16.4	264.2	2.1	389.8	301.2	11.4	-2.0%	b1-NaCl +
285	78	1252	7.3	34.6	18.1	229.0	1.9	436.2	170.2	15.3	3.8%	f1-NaHCO3+
287	60	1297	7.3	44.5	18.9	229.0	1.6	431.5	160.4	62.8	3.3%	f1-NaHCO3+

294	114	1387	7.4	70.5	6.1	290.0	4.8	492.9	240.0	24.2	4.4%	f2-NaHCO3+
453	60	4050	7.2	62.7	57.9	459.3	3.3	227.4	570.2	668.2	-9.4%	b2-NaMix +
461	4.7	407	6.5	24.2	28.5	5.7	1.1	208.7	20.0	2.0	-2.5%	F1-MgHCO3+
466	6.3	540	6.9	49.2	20.2	17.5	2.2	252.2	28.0	2.3	-0.4%	F2-CaHCO3+
510	189	864	6.9	52.4	38.0	62.1	3.9	456.5	55.6	8.7	-3.9%	F2-MgHCO3+

Section Brebes/Tegal III

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
22	5.8	6300	8.0	384.5	228.0	972.9	12.4	496.9	1069.8	2380.4	-4.3%	B5-NaSO4 +
37	8.4	6450	8.0	239.3	246.5	1029.9	9.3	843.2	393.5	2920.3	-5.2%	b5-NaSO4 +
39	8	1569	8.2	106.9	62.1	179.0	14.7	618.7	131.9	270.0	-2.3%	F3-CaHCO3+
43	5	3510	8.0	291.1	114.7	508.0	25.6	607.0	314.0	1391.9	-1.1%	b4-CaSO4 +
45	10.4	3800	8.0	292.5	128.1	482.1	15.1	335.0	623.9	1296.8	-3.7%	b4-CaSO4 +
107	2	2150	7.3	30.2	51.5	309.3	4.8	413.1	480.0	15.1	-3.3%	b2-NaCl +
110	4	1660	7.2	62.5	75.0	189.0	6.0	656.5	230.0	17.1	0.2%	f3-MgHCO3+
111	92	1880	7.3	40.3	17.8	308.9	2.5	561.0	232.0	77.5	-1.1%	f1-NaHCO3+
112	6	3490	7.4	226.7	50.3	413.0	11.3	936.1	620.0	90.7	-1.5%	b3-NaCl +
113	96	1800	7.6	30.2	9.1	311.2	1.9	456.5	246.0	78.3	-0.7%	f1-NaMix +
116	15	8250	7.0	53.2	64.4	2160.1	4.1	1095.7	2700.0	93.0	2.8%	B2-NaCl +
118	13	10040	7.5	176.3	199.9	1740.0	30.5	1231.6	2900.0	108.2	-1.2%	B4-NaCl 0
122	93	1415	7.5	22.2	8.2	290.1	1.6	500.0	156.0	74.3	1.0%	f0-NaHCO3+
123	82	1300	7.5	18.1	5.7	276.0	1.8	552.2	138.0	59.1	-2.7%	F0-NaHCO3+
127	7.2	2250	8.2	65.9	67.9	442.1	4.3	893.2	210.0	383.0	-0.6%	f3-NaHCO3+
130	15	2270	7.6	95.7	60.3	353.0	11.3	1010.0	150.0	86.5	5.8%	F3-NaHCO3+
131	6	5860	7.0	211.6	154.6	340.7	2.7	704.4	384.0	879.2	-3.2%	b4-MgMix +
133	8.6	6450	8.1	217.4	270.6	1520.0	6.0	917.6	435.0	3293.9	1.8%	b5-NaSO4 +
134A	7.4	1040	8.0	90.4	50.7	86.0	14.0	584.0	41.0	76.6	1.8%	F3-CaHCO3+
134	7.5	2490	6.9	120.9	43.7	311.2	4.0	647.9	408.0	131.5	-3.3%	b3-NaMix +
135	8	1820	7.0	64.5	47.3	221.9	1.4	530.5	218.0	112.7	-1.2%	f2-NaHCO3+
139	96	2020	7.3	24.2	9.8	330.0	0.9	378.3	366.0	161.6	-9.6%	b1-NaCl +
192	48	1550	7.2	32.2	23.7	271.3	1.9	595.7	178.4	17.6	0.8%	f1-NaHCO3+
509	9	2850	6.9	106.8	44.3	348.8	2.8	613.1	162.0	521.7	-2.5%	f3-NaMix +

Shallow wells (depth < 15 m.) in Brebes/Tegal

Iden	Depth	ECfld	pH	Ca	Mg	Na	K	HCO3	Cl	SO4	Bal. Error	Hydrochemical Type
9	9	882	7.4	44.1	25.3	79.5	9.5	275.9	14.8	135.3	1.4%	F2-CaHCO3+
17	7.1	1309	8.0	112.7	32.6	85.0	105.0	455.0	115.0	179.0	0.9%	F3-CaHCO3+
18	8.2	3160	7.6	169.0	26.9	196.7	76.5	452.4	218.1	266.8	5.1%	f3-CaMix +
22	5.8	6300	8.0	384.5	228.0	972.9	12.4	496.9	1069.8	2380.4	-4.3%	B5-NaSO4 +
22	9.8	7010	7.5	291.5	137.6	1089.5	11.9	962.8	1096.0	689.0	9.3%	B4-NaCl +
33	4.2	2660	7.6	113.0	129.1	288.0	9.0	724.4	254.8	469.3	0.3%	f4-MgMix +
37	8.4	6230	7.6	211.9	129.5	1135.4	9.3	777.2	396.5	2023.7	3.5%	b4-NaSO4 +
37	8.4	6450	8.0	239.3	246.5	1029.9	9.3	843.2	393.5	2920.3	-5.2%	b5-NaSO4 +
39	8	1400	7.7	86.6	64.7	121.1	9.8	603.2	131.0	212.7	-8.6%	F3-MgHCO3+
39	8	1569	8.2	106.9	62.1	179.0	14.7	618.7	131.9	270.0	-2.3%	F3-CaHCO3+
43	5	3510	8.0	291.1	114.7	508.0	25.6	607.0	314.0	1391.9	-1.1%	b4-CaSO4 +
45	10.4	3800	8.0	292.5	128.1	482.1	15.1	335.0	623.9	1296.8	-3.7%	b4-CaSO4 +
45	10.3	8110	7.7	197.9	136.6	530.1	10.7	336.4	591.2	1309.7	-5.3%	b4-NaSO4 +
69	5.4	2890	7.2	387.6	191.1	1182.3	6.1	452.4	2095.9	1193.8	-2.7%	B5-NaCl 0
87	5	2930	7.9	220.2	129.5	409.9	1.4	679.7	444.9	898.0	-3.5%	b4-CaMix +
115	9	707	7.3	123.7	23.1	30.5	31.4	348.3	53.3	135.3	0.9%	F3-CaHCO3+
119	10.2	1887	7.9	66.0	44.9	313.0	7.3	522.5	101.8	452.2	-0.1%	F2-NaMix +
125	7.9	1898	7.3	98.9	95.9	204.3	9.5	589.9	187.2	352.5	-0.8%	f3-MgMix +
127	7.2	2250	8.2	65.9	67.9	442.1	4.3	893.2	210.0	383.0	-0.6%	f3-NaHCO3+
133	8.6	6450	8.1	217.4	270.6	1520.0	6.0	917.6	435.0	3293.9	1.8%	b5-NaSO4 +
134	7.3	1230	7.4	78.3	51.8	84.9	26.7	539.3	50.9	55.1	4.7%	F3-MgHCO3+
134	7.4	1040	8.0	90.4	50.7	86.0	14.0	584.0	41.0	76.6	1.8%	F3-CaHCO3+
220	9	2830	8.0	62.6	34.7	577.0	2.2	677.9	399.9	472.0	-1.7%	b2-NaMix +

REFERENCES

Allison, G.B. & M.W. Hughes, 1983. The use of natural tracers as indicators of soil-water movement in temperate semi-arid region. Journ. of Hydrol. 60 (1983), pp. 157-173.

Bakhoven, H.G.A., 1936. De bevloeiing van de vlakte van Noord-Krawang uit de Tjitaroem. De Ingenieur in Nederlandsch-Indië, VI. Waterbouwkunde, 3e jaargang, nummer 7, juli 1936.

Barnes, C.J. & G.B. Allison, 1983. The distribution of deuterium and ^{18}O in dry soils. Journ. of Hydrol. 60 (1983), pp. 141-156.

Bartstra, G & W.A. Casparie, 1976. Modern Quaternary Research in Southeast Asia, Volume 2. A.A. Balkema, The Netherlands, Rotterdam, 1976. 66 pp.

Batchelor, B.C., 1979. Discontinuously rising Late Cenozoic eustatic sea-levels, with special reference to Sundaland, Southeast Asia. Geologie en Mijnbouw, vol. 58, nr. 1, pp. 1-20.

Beaudet, G., R. Coque, P. Michel & P. Rognon, 1981. Reliefs cuirasses et evolution geomorphologique des regions orientales du Mali. Le Gourma et le Plateau de Bandiagara, son contact avec le Macina. Z. Geomorph. N.F., Suppl.-Bd 38, Berlin, Stuttgart, Juni 1981, pp. 1-37.

Besler, H., 1985. Untersuchungen zur Reliefgenese in die immerfeuchten Tropen (Kalimantan Timur/Borneo). Z. Geomorph. N.F., suppl.-Bd. 56, Berlin-Stuttgart, pp. 13-30.

Bhattacharya, C.G., 1967. A simple method of resolution of a distribution into Gaussian components. Biometrics, March 1967, pp. 115-129.

Billings, G.K. & H.H. Williams, 1967. Distribution of chlorine in terrestrial rocks (a discussion). Geochim. Cosmochim. Acta, 31, p.2247, London, New York.

Binnie and Partners, 1982. Central Java Groundwater Survey, DPU-DPMA. Vol. 9. Zonal report Pemali-Comal. B. & Partners in assoc. with Hunting Technical Services under assignment to the Overseas Development Administration, London. Interim report 1982.

Bird, E.C.F., 1984. Coasts; An introduction to coastal geomorphology. Third edition. Basil Blackwell Publisher Limited, England. 306 pp.

Birkeland, P.W., 1974. Pedology, Weathering, and Geomorphological Research. New York Oxford University Press, London, Toronto, 1974.

Biswas, B., 1973. Quaternary changes in sea-level in the South China Sea. Geol. Soc. Malaysia, 6, July 1973, pp. 229-256.

Blatt, H., 1982. Sedimentary Petrology. W.H. Freeman and Company, San Francisco 1982.

Bloom, A.L., W.S. Broecker, J.M.A. Chappell, R.K. Matthews & K.J. Mesolella, 1974. Quaternary sea level fluctuations on a tectonic coast: new $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea. Quat. Res., 4, pp. 185-205.

Boerman, W.E., 1949. Klimaat, klimaattypen - klimaatgebieden - bodemproductie - bevolking. Noorduijn's wetenschappelijke reeks, No. 25. J.Noorduijn en Zoon N.V.

Braak, C., 1919. Atmospheric variations of short and long duration in the Malay Archipelago and neighbouring regions and the possibility to forecast them. Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia, Verhandelingen No. 5. Javasche boekhandel en drukkerij, Batavia, 1919.

Braudel, F., 1977. Captalism and Material Life 1400-1800. Translated by Miriam Kochan. Fontana/Collins, Glasgow, Britain.

Chorley, R.J., S.A. Schumm & D.E. Sugden, 1984. Geomorphology. Methuen & Co., London and New York.

Clark, I., 1977. Roke, a computer program for nonlinear least squares decomposition of mixtures of distributions. Computers & Geosciences, Vol. 3, 1977, pp. 245-256.

Clark, J.A. et al., 1978. Global Changes in Postglacial Sea Level: A numerical calculation. Quaternary Research 9, pp. 265-287.

Clark, M.W., 1976. Some methods for statistical analysis of multimodal distributions and their application to grain size data. Jour. Math. Geology, v.8, no.3, pp. 267-282.

Cloetingh, S. & R. Wortel, 1985. Regional stress field of the Indian plate. Geophysical Research Lett. 12, pp. 77-80.

Cloetingh, S., 1986. Tectonics of passive margins: implications for the stratigraphic record. Geologie en Mijnbouw 65: pp. 103-117 (1986).

Condon H.W., L. Pardyanto & K.B. Ketner, 1975. Geological map of the Banjanegara and Pekalongan Quadrangles, Java. Geological Survey of Indonesia, Bandung.

Dawkins, R., 1988. The blind watchmaker. Penguin Books, London, 1988, 326 pp.

De Goffau, A. & P. Van Der Linden, 1982. Late Tertiary and Quaternary coastal landscape development of the Kroya beach ridge area (south central Java, Indonesia). Geologie en Mijnbouw 61, pp. 131-140.

De Jongh, C.A., 1923. Verslag over de mogelijkheid van een artesisch drinkwatervoorziening van Tegal. Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.

De Klerk, L.G., 1983. Zeespiegels, Riffen en Kustvlakten in Zuidwest Sulawesi, Indonesië; een Morfogenetische-Bodemkundige studie. Ph.D. Thesis, University of Utrecht. Geographical Institute, University of Utrecht, The Netherlands, 119 pp.

De Neve, G.A., 1950. Notitie over vertebraat-fragmenten uit de proefboring Kebajoran. De Ingenieur in Indonesië, No.5, 1950.

De Ruiter, J.C., 1988. Hydrologische systeemanalyse van Zuid-Holland, TNO-DGV, Delft.

Deer, W.A., R.A. Howie & J. Zussman, 1972. An introduction to the rock-forming minerals. Sixth impression. Longman Group limited, London. 518 pp.

Dick, N.P. & D.C. Bowden, 1973. Maximum likelihood estimation for mixtures of two normal distributions. Biometrics v.29, pp. 781-790.

Dietz, R.S. & J.C. Holden, 1970. The breakup of Pangaea. In 'Continents adrift and Continents aground', with introductions by Wilson J.T., Scientific American, 1963-1976. Freeman W.H. and Company, San Fransisco.

Djoehanah, S., 1984. Stratigrafi sumor bor artesis Pamanukan dan relevansinya untuk pengetahuan hidrogeologi dan stratigrafi Kuarter dataran pantai utara Jawa Barat. Internal report, National Institute for Geology and Mining, LIPI, Bandung.

Djuri, M., 1973. Geological map of the Ardjawinangun Quadrangle, Java. Scale 1 : 100,000. Geological Survey of Indonesia, Bandung.

Djuri, M., 1975. Geological map of the Purwokerto and Tegal Quadrangles, Java. Scale 1 : 100,000. Geological Survey of Indonesia, Bandung.

Domenico, P.A., 1972. Concepts and models in groundwater hydrology. McGraw-Hill. New York.

Dooge, J.C.I., 1973. Linear theory of hydrologic systems. Tech. Bul. No. 1468, USDA Agricultural Research Service, Beltsville, Maryland.

Douglas, I. & T. Spencer (editors), 1985. Environmental Change and Tropical Geomorphology. A publication of the British Geomorphological Research Group. George Allen & Unwin, London, 378 pp.

Emiliani, C., 1972. Quaternary paleotemperatures and the duration of the high-temperature intervals. Science 178, pp. 398-401.

Engelen, G.B., 1973. Preliminary scientific results : A working hypothesis on the relation between soil formation and geological and morphological history of the Serayu Valley area. In : Report on the visit to the Serayu Valley Project from October 14th till November 6th, 1973, pp. 25-28.

Engelen, G.B., 1980. Hydrologische indeling van Nederland. Een regionale, systeemanalytische benadering. In : Waterkwaliteit in grondwaterstromingsstelsels. CHO-TNO. Rapporten en nota's 5, 29-36, Den Haag.

Engelen, G.B., 1984. Hydrological system analysis. A regional case study. Arnhem east. Report OS 94-20. TNO-DGV Institute of Applied Geoscience. Delft, Netherlands.

Engelen, G.B. & G.P. Jones (editors), 1987. Developments in the analysis of groundwater flow systems. Intern. Assoc. of Hydr. Sciences, publication No. 163. A contribution to the International Hydrological Programme of UNESCO, project A 2.8.

Engelen, G.B., J.M.J. Gieske & S.O. Los., 1988. Grondwater stromingsstelsels in Nederland (werkdocument). Achtergronddocument t.b.v het Nationaal Natuur Beleidsplan. NMF, SBB en Instituut voor Aardwetenschappen. SSB rapport 1988-36. pp. 162.

Engelen, G.B. & R.G.W. Venneker, 1988. ETA (Erosion, Transport, Accumulation) systems, their classification, mapping and management. IAHS Publ., 174, pp. 397-412.
Fairbridge, R.W., The Encyclopedia of Geochemistry and Environmental Sciences. Encyclopedia of Earth Sciences Series, Volume IV A. Dowden, Hutchinson & Ross, Inc. Stroudsburg Pennsylvania.
Fairbridge, R.W., The Encyclopedia of Geomorphology. Encyclopedia of Earth Sciences Series, Volume III. Reinhold Book Corporation. New York-Amsterdam-London.
Fetter, C.W. Jr., 1980. Applied hydrogeology. Charles E. Merrill Publishing Company.
Fisher, C.A., 1971. South-East Asia; A social, economic and political geography. London: Methuen & Co. Ltd. 777 pp.
Flenley, J.R. & R.J. Morley, 1978. A minimum age for the deglaciation of Mt. Kinabalu, East Malaysia. Mod. Quaternary Res. SE Asia, 4 (1978), pp. 57-61.
Fontanel, J. & A. Chantefort, 1978. Bioclimats du monde Indonesien. Institut Francais de Pondichery, Inde. First edition, 1978.
Frakes, L.A., 1979. Climates Throughout Geologic Time. Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York, 1979. 310 pp.
Fritz, P. & J.CH. Fontes, 1980. Handbook of Environmental Isotope Geochemistry. Vol. I, The Terrestrial environment, A. Elsevier Scientific Publishing Comp., Amsterdam. pp. 544.
Gates, W.L., 1976. Modelling of ice-age climate. Science, 191, pp. 1138-1144.
Geertz, C., 1970. Agricultural involution; the process of ecological change in Indonesia. Berkeley/Los Angeles, University of California Press 1970. 170 pp.
Geller, C.A., J.K. Weissel & R.N. Anderson, 1983. Heat transfer and intraplate deformation in the central Indian Ocean. J. Geophys. Res. 88, pp. 1018-1032.
Geyh, M.A., H.R. Kudrass & H. Streif, 1979. Sea-level changes during the late Pleistocene and Holocene in the Strait of Malacca. Nature, Vol. 278, No. 5703 (1979), pp. 441-443.
Gilliot, J.E., 1968. Clay in engineering geology. Elsevier Publishing Comp, Amsterdam. pp. 280.
Gischler, M.A., 1988. Survey of strongly mineralized groundwaters in the coastal lowlands of the kabupaten Brebes, Central Java, Indonesia. Unpublished M.Sc. thesis, Faculty of Earth Sciences, Free University, Amsterdam.
Hamilton, W., 1979. Tectonics in the Indonesian region, U.S. Geol. Survey Prof. Paper 1078, 345 pp., 1979.
Hardjono, J., 1971. Indonesia, Land and People, Djakarta, P.T. Gunung Agung, 272 pp.
Hasudungan, T., 1987. Model hidrostratigrafi sebagai suatu pendekatan studi air tanah regional pada dataran aluvial pantai, Kabupaten Tegal, Jawa Tengah. Unpublished S1 thesis (Indonesian), Faculty of Geography, Gadjah Mada University, Yogyakarta, Indonesia.
Hehanussa, P.E. & F. Hehuwat, 1979. Morphogenesis of the northern coastal plain of West Java between Cirebon and Jakarta: Its implications for coastal zone management. Proceedings of the Jakarta workshop on coastal resource management, 11-15 september, 1979. The United Nations University.
Hehanussa, P.E. 1979. Excursion guide to the Cimanuk Delta, West Java. Proceedings of the Jakarta workshop on coastal resource management, 11-15 september, 1979. The United Nations University.
Hehanussa, P.E., 1979. Penyusuapan air laut ke dalam cekungan artois Jakarta (Saltwater encroachment in the Jakarta artesian basin). Paper presented at 5th. Ann. Conv. Indon. Geol. Assoc.
Heilmann, P.G.F., 1972. On the formation of red soils in the Lower Crati basin (S. Italy). Publication of the International soil museum Utrecht, the Netherlands.
Heine, K., 1981. Aride und pluviale Bedingungen während der letzten Kaltzeit in der Südwest-Kalahari (südliches Afrika). Ein Beitrag zur klimagenetischen Geomorphologie der Dünen, Pfannen und Täler. Z. Geomorph. N.F., Suppl.-Bd 38., Berlin, Stuttgart, Juni 1981, pp. 1-37.
Hilde, T.W.C., 1983. Sediment subduction versus accretion around the Pacific. Tectonophysics, 99 (1983), pp. 381-397.

Hilde, T.W.C., S. Uyeda & L. Kroenke, 1977. Evolution of the western Pacific and its margin. Tectonophysics, 38, (1977), pp. 145-165.
Hinch, H.H. in W.H. Roberts & R.J. Cordell (ed.) 1980. Problems of petroleum migration. AAPG studies in geology No. 10. AAPG, Tulsa, Oklahoma, 74101, USA.
Hoel, P.G., 1962. Introduction to mathematical statistics. Third edition. John Wiley & Sons, New York. 428 pp.
Honza, E., 1983. Evolution of arc volcanism related to marginal sea spreading and subduction at trench. In Arc Volcanism: Physics and Tectonics, edited by D. Shimozuro and I. Yokoyama, pp. 177-189. Terra Scientific Publishing Company (TERRAPUB), Tokyo.
Hopley, D, 1986. Beachrock as a sea-level indicator. In 'Sea-level research; a manual for the collection and evaluation of data', edited by Van den Plassche, 1986, pp. 157-173. Geo Books, Norwich.
Hunt, C.B., 1972. Geology of Soils. Their Evolution, Classification, and Uses. W.H. Freeman and Company, San Francisco 1972.
I Made Sandy, 1982. Atlas Indonesia, Buku Pertama Umum. Jurusan Geografi, FIPIA, U.I, 5th edition, February, 1982.
Ida, Y., 1983. Thermal and mechanical processes producing arc volcanism and back-arc spreading. In Arc Volcanism: Physics and Tectonics, edited by D. Shimozuro and I. Yokoyama, pp. 165-175. Terra Scientific Publishing Company (TERRAPUB), Tokyo.
Iwaco/Waseco, 1987a. Groundwater resources survey in West Java; Interim report. Ministry of public works, Directorate general for human settlement, Jakarta.
Iwaco/Waseco, 1987b. Groundwater reconnaissance study, Kabupaten Bekasi. Ministry of public works, Directorate general for human settlement, Jakarta.
Janssen, J.H.W. & M.A.C. Dam, 1985. The Quaternary geological map 1:50,000 of the Jatibarang area, West Java; Field Survey report. Unpublished M.Sc. thesis, Institute for Earth Sciences, Free University, Amsterdam.
Karmono Mangunsukardjo, 1984. Inventarisasi sumberdaya lahan di daerah aliran sungai Serayu dengan tinjauan secara geomorfologi. Ph.D. Thesis, Universitas Gadjah Mada, Yogyakarta, 1984.
Kastowo, 1975. Geological map of the Majenang Quadrangle, Central Java. Scale 1 : 100,000. Geological Survey of Indonesia, Bandung.
Katili, J.A. & H.D. Tjia, 1969. Outline of Quaternary tectonics of Indonesia. Bull. Nat. Inst. Geol. and Mining, vol. 2, no. 1, pp1-10.
Katili, J.A., 1975. Volcanism and plate tectonics in the Indonesian island arcs. Tectonophysics, 26, (1975), pp. 165-188.
Kershaw, A.P., 1976. A Late Pleistocene and Holocene pollen diagram from Lynch's Crater, northeastern Queensland, Australia. New Phytol. 77, pp. 469-498.
Kidson, C., 1986. Sea-level changes in the Holocene. In 'Sea-level research; a manual for the collection and evaluation of data', edited by Van den Plassche, 1986, pp. 27-64. Geo Books, Norwich.
Kienle, J., S.E. Swanson & H. Pulpan, 1983. Magmatism and Subduction in the Eastern Aleutian Arc. In Arc Volcanism: Physics and Tectonics, edited by D. Shimozuro and I. Yokoyama, pp. 191-224. Terra Scientific Publishing Company (TERRAPUB), Tokyo.
Kloosterman, F.H., 1986. Groundwater investigations in the northern coastal plain of West- and Central Java. Symposium Lowland Development in Indonesia, 24-31 August 1986, Jakarta. International Institute for Land Reclamation and Improvement/ILRI, Wageningen, Holland.
Kobayashi, K., 1983. Fore-Arc Volcanism and Cycles of Subduction. In Arc Volcanism: Physics and Tectonics, edited by D. Shimozuro and I. Yokoyama, pp. 153-163. Terra Scientific Publishing Company (TERRAPUB), Tokyo.
Koch, G.S. jr. & R.F. Link, 1980. Statistical analysis of geological data. Vol. I and II, 438 pp., Dover Publications, Inc, New York.
Koesoemadinata, S. & M. Situmorang, 1985. Quaternary Geologic map of the Bekasi Quadrangle, Jawa. Scale 1:50,000. Systematic Quaternary Geologic Map of Indonesia. Geological Research and Development Centre, Bandung, Indonesia.

Koesoemadinata, S., M. Situmorang & D.M. Barmawidjaja, 1985. Quaternary Geologic map of the Batujaya & Galian Quandrangle, Jawa. Scale 1:50,000. Systematic Quaternary Geologic Map of Indonesia. Geological Research and Development Centre, Bandung, Indonesia.

Kohout, F.A. et al., 1977. Fresh ground water stored in aquifers under the continental shelf: Implications from a deep test well, Nantucket island, Massachusetts. Water Resources Bull. 13 (1977), pp. 373-386.

Kominz, M.A., 1984. Oceanic ridge volumes and sea level change - an error analysis, in International Unconformities and Hydrocarbon Accumulations, J. Schlee Ed., Amer. Assoc. Petrol. Geol. Memoir, 1984.

Koolhoven, W.C.B., 1934. Verslag van een tocht in blad 35 (Soebang) in September 1934. Dienst van den Mijnbouw in Nederlandsch-Indië. Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.

Koopmans, B.N. & P.H. Stauffer, 1968. Glacial phenomena on Mt. Kinabaluh, Sabah, Borneo region, Malaysian Geol. Survey Bull. 8: pp. 25-35.

Kraus, E.B., 1973. Comparison between ice age and present general circulation. Nature, 245, pp. 129-133.

Krauskopf, B.K., 1985. Introduction to geochemistry, 2nd. edition. International student edition. McGraw-Hill Book Company. 600 pp.

Le Pichon, X., J. Francheteau & J. Bonnin, 1976. Plate tectonics. Developments in Geotectonics 6, 2nd. edition. Elsevier Scientific Publishing Co., Amsterdam.

Le Pichon, X., P. Huchon & E. Barrier, 1985. Pangea, Geoid and the Evolution of the Western Margin of the Pacific Ocean. In Formation of Active Ocean Margins, edited by N. Nasu et al., pp. 3-42. Terra Scientific Publishing Company (TERRAPUB), Tokyo.

Lister, C.R.B., 1975. Gravitational drive on oceanic plates caused by thermal contraction. Nature 257, pp. 663-665.

Lowe, J.J. & M.J.C. Walker, 1984. Reconstructing Quaternary Environments. Longman, London and New York.

Marks, P., 1956. Foraminifera ketjil dari Sumur no. 1 di Kebayoran, Jakarta. Publikasi Keilmuwan 30, Seri Paleontologi, Djawa Geologi, Kementerian Perekonomian R.I., Bandung.

Marsh, B.D., 1979. Island-arc volcanism. American Scientist No. 67, pp. 161-172.

McKenzie, D.P. & J.G. Sclater, 1973. The evolution of the Indian Ocean. In 'Continents adrift and Continents aground', with introductions by Wilson J.T., Scientific American, 1963-1976. Freeman W.H. and Company, San Fransisco.

Meinardi, C.R., 1976. Geohydrological features of the kecamatan Krangkeng, Kab. Indramayu. OTA-33 report, No. 3, IWACO BV., Bandung.

Meinardi, C.R., 1976. Hydrogeological considerations with regard to drinking water supply and land improvement in Desa Totoran (Kabupaten Indramyu), OTA-33 report, No.9, IWACO BV., Bandung.

Meinardi, C.R., 1976. The hydrological situation of desa Cikawung, Kab. Indramayu, with regard to public water supply. OTA-33 report, No. 4, IWACO BV., Bandung.

Meinardi, C.R., 1977. First notes on the groundwater situation in Kabupaten Tangerang, OTA-33 report, No. 15, IWACO BV., Bandung.

Meinardi, C.R., 1977. Groundwater resources of kecamatan Losarang, Kab. Indramayu. OTA-33 report, No. 13, IWACO BV., Bandung.

Meinardi, C.R., 1977. Preliminary notes on the groundwater situation in Kabupaten Karawang, OTA-33 report, No. 16, IWACO BV., Bandung.

Mook, W.G., 1984. Principles of isotope hydrology. Department of Hydrogeology and Geographical hydrology, Free University, Amsterdam.

Morgan, W.J., 1972. Deep mantle convection plumes and plate motions. Am. Assoc. Petrol. Geol., 56, pp. 203-213.

Morley, R.J., 1981. Development and vegetation dynamics of a lowland ombrogenous peat swamp in Kalimantan Tengah, Indonesia. Journal of Biogeography, 8, pp. 383-404.

Norušis, M.J., 1986. SPSS/PC+ & SPSS/PC+ advanced statistics. SPSS inc., Chicago.

Orchiston, D.W. & W.G. Siesser, 1982. Chronostratigraphy of the Plio-Pleistocene fossil hominids of Java. Mod. Quaternary Res. SE Asia (1982), pp. 131-149.
Pádmosukismo, S. & I. Yahya, 1974. The basement configuration of the North West Java area. Proc. Indon. Petroleum Assoc., 3rd. annual conv., Jakarta.
Pannekoek, A.J., 1949. Outline of the geomorphology of Java. Tijdschr. Kon. Ned. Aardr. Gen., 66. pp. 270-326.
Petit, J.R, M. Briat & A. Royer, 1981. Ice age aerosol content from East Antarctic ice core samples and past wind strengths. Nature 293, pp. 391-394.
Pettijohn, E.J., 1975. Sedimentary rocks. Third edition. Harper & Row , publishers, New York. 598 pp.
Pramono, 1981. Konservasi air tanah daerah pantai utara Jawa Barat, Laporan tahunan 1980/1981, Direktorat Geologi Tata Lingkungan.
Purbo-Hadiwidjoyo, M.M., 1977. The status of groundwater research and development in Indonesia 1975. Geologi Indonesia, J4, Nr. 1, 1977.
Reading, H.G., (editor), 1982. Sedimentary environments and facies. Blackwell Scientific Publications, Oxford, Londen. 556 pp.
Reineck, H.-E. & I.B. Singh, 1975. Depositional Sedimentary Environments; with reference to terrigenous clastics. Springer-Verlag, Berlin Heidelberg New York, 1975. 439 pp.
Riezebos, H. Th., 1984. Geomorphology and savannisation in the Upper Sipaliwini River basin (S. Suriname). Z. Geomorph. N.F., 56, Heft 3, Berlin-Stuttgart, pp. 265-284.
Rimbaman, A.L. Spaanderman & T.B. Van der Werf, 1986. The Quaternary geological map 1:50,000 of the Cilamaya area, West Java; Field Survey report. Unpublished M.Sc. thesis, Institute for Earth Sciences, Free University, Amsterdam.
Roberts, W.H. & R.J. Cordell, 1980. Problems of petroleum migration. AAPG studies in geology, No. 10. AAPG, Tulsa, Oklahoma, 74101, USA, 1980.
Sarmiento, G. & M. Monasterio, 1975. A critical consideration of the environmental conditions associated with the occurrence of savanna ecosystems in tropical America. In : Golley, F.B. & E. Medina (eds.): Tropical ecological systems. Ecol. Stud. 11, Springer, New York-London-Heidelberg, pp. 223-250.
Sarthein, M., F. Tetzlaff, B. Koopman, K. Wolter & U. Pflaumann, 1981. Glacial and interglacial wind regimes over the eastern subtropical Atlantic and North-West Africa. Nature 272, pp. 43-45.
Sartono, S., 1984. Notes on the Pleistocene Stratigraphy of Java, Indonesia. Mod. Quaternary Res. SE Asia (1983/1984), pp. 129-135.
Sayles, F.L. & F.T. Manheim, 1975. Interstitial solutions and diagenesis in deeply buried marine sediments: results from the Deep Sea Drilling Project. Geochim. Cosmochim. Acta, 1975, Vol. 39, Pergamon Press, pp. 103-127.
Scales, L.E., 1985. Introduction to non-linear optimization. Macmillan Computer Science series. Macmillan publishers Ltd., London. 243 pp.
Semah, A., 1982. A preliminary report on a Sangiran pollen diagram. Modern Quaternary Research SE Asia 7 (1982), pp. 165-170.
Seuffert, O., 1978. Leitlinien der Morphogenese und Morphodynamik im Westsaum Indiens. Z. Geomorph. N.F., Suppl.Bd 30, Berlin. Stuttgart, Oktober 1978, pp. 143-161.
Sharma, K.K., 1987. Crustal growth and two-stage India-Eurasia collision in Ladakh. Tectonophysics, 134 (1987), pp. 17-28. Elsevier Publishers B.V., Amsterdam.
Shimozuru, D. & N. Kubo, 1983. Volcano Spacing and Subduction. In Arc Volcanism: Physics and Tectonics, edited by D. Shimozuro and I. Yokoyama, pp. 141-151. Terra Scientific Publishing Company (TERRAPUB), Tokyo.
Silitonga, P.H. & Memed Masria, 1978. Geological map of the Cirebon Quadrangle, West Java. Scale 1 : 100,000. Geological Survey of Indonesia, Bandung.
Silitonga, P.H., 1973. Geological map of the Bandung Quadrangle, West Java. Scale 1 : 100,000. Geological Survey of Indonesia, Bandung.
Simmers, I. (editor), 1988. Estimation of natural groundwater recharge. NATO ASI series, Series C: Mathematical and physical sciences, Vol. 222. pp. 508.

Smit Sibinga, G.L., 1949. Pleistocene eustasy and glacial chronology in Java and Sumatra. Verh. K. Ned. Geol. Mijnbouw Gen Geol. Serie 15/1, p1-31.
Smit Sibinga, G.L., 1950. Marine falls and their significance with regard to the power ratio between marine and fluvial destruction. Geol. Mijnbouw, 11: pp. 321-323.
Smit Sibinga, G.L., 1951. On the origin and the age of the peneplain of Palembang. Geol. Mijnbouw, 13: pp. 1-11.
Smit Sibinga, G.L., 1952. Interference of glacial eustasy with crustal movements and rhythmic sedimentation in Java and Sumatra. Geol. Mijnbouw, 14: pp. 220-225.
Smit Sibinga, G.L., 1953. Pleistocene eustasy and glacial chronology in Borneo. Geol. Mijnbouw, 11: pp. 365-383.
Soefner, B., M. Hobler & G. Schmidt, 1986. Jakarta groundwater study; final report. HAG 117, Vol. 8 (1985), German Hydrogeological Advisory Group in Indonesia (CTA 40), Directorate of Environmental Geology, Bandung.
Soekardi, R. & M. Koesmono, 1973. Pengamatan neotektonik dan morfogenese di daerah daratan Jakarta (Neotectonic and morphogenetic observations in the Jakarta area). Unpublished report Geol. Surv. of Indonesia, No. 1799.
Soekardi, R. & M.M. Purbo-Hadiwidjoyo, 1979. Cekungan artois Jakarta (The Jakarta artesian basin). Geol. Indon. 2 (1).
Soekardi, R., 1972. Aspek geologi terhadap perkembangan pantai dan tata air tanah daerah Jakarta. Sarjana thesis, Jurusan Geologi, Fakultas Ilmu Pasti dan Pengetahuan Alam, Universitas Padjadjaran, Bandung.
Soetomo, J.A. & F.X. Sujanto, 1978. The oil discovery in well KHT-3 with special notes on its seismic characteristics. Geologi Indonesia, J.5, No.1, 1978.
Speelman, H., 1978. Geology, Hydrogeology and engineering geological features of the Serayu river basin, Central Java, Indonesia. Serayu Valley Project, Final Report volume 4. NUFFIC Project ITC/GUA/VU.
Stumm, W. & J.J. Morgan, 1981. Aquatic chemistry; an introduction emphasizing chemical equilibria in natural waters. 2nd ed. John Wiley & Sons.
Stuyfzand, P.J., 1986. A new hydrochemical classification of water types: Principles and application to the coastal dunes aquifer system of the Netherlands. Salt Water Intrusion Meeting, 9, Delft May 12-16, 1986.
Stuyfzand, P.J., 1988. Hydrochemical evidence of fresh and salt water intrusion in the coastal dune aquifer system of the Western Netherlands. Proc. SWIM 10 Symposium, Gent 1988, Natuurwetenschappelijk tijdschrift.
Sulistiyanto, E., 1987. Penyebaran tipe kimia air tanah di Kabupaten Tegal, Jawa Tengah. Unpublished S1 thesis (Indonesian), Faculty of Geography, Gadjah Mada University, Yogyakarta, Indonesia.
Sutarso, B. & S. Padmosukismo, 1978. The diapiric structures and their relation to the occurrence of hydrocarbon in North-East Java basin. Geologi Indonesia, J. 5, No. 1, 1978.
Ter Haar, C, 1930. Maandrapport over de maand Juli, 1930. Dienst van den Mijnbouw in Nederlandsch-Indië. Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.
Ter Haar, C, 1932. Maandrapport over Februari, 1932. Verkenning in de omgeving van Bandjarhardja, Tjisadap en Karangbale. Dienst van den Mijnbouw in Nederlandsch-Indië. Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.
Ter Haar, C., 1928. Geologische opname in het stroomgebied van de Tjipamali en Tjigunung, Maandrapport September, 1928. Dienst van den Mijnbouw in Nederlandsch-Indië. Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.
Ter Haar, C., 1935. Geologische kaart van Java, toelichting bij blad 58 (Boemiajoe), scale 1:100,000. Dienst van den Mijnbouw in Nederlandsch-Indië. Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.
Terzaghi, K. & R.B. Peck, 1967. Soil mechanics in engineering practice. Second edition. Wiley and sons, Inc., New York, 702 pp.

Thaden, R.E., Harli Sumadirdja & P.W. Richards, 1975. Geological map of the Magelang and Semarang Quadrangles, Central Java. Scale 1 : 100,000. Geological Survey of Indonesia, Bandung.

Thommeret J, & Y. Thommeret, 1978. ^{14}C datings of some Holocene sea levels on the north coast of the island of Java (Indonesia). Mod. Quaternary Res. SE Asia, 4 (1978), pp. 51-56.

Tjia, H.D. et al., 1983. Holocene shorelines in the Indonesian tin islands. Mod. Quaternary Res. SE Asia, 8 (1983/1984), pp. 103-117.

Tjia, H.D., 1965. Course changes in the lower Cimanuk river. Geological Survey of Indonesia, Bandung.

Tjia, H.D., S. Asikin & R.S. Atmadja, 1968. Coastal accretion in western Indonesia. Bulletin of the National Institute of Geology and Mining, Bandung. Volume 1-1, pp. 15-45.

Toth, J., 1962. A theory of groundwater motion in small drainage basins in Central Alberta, Canada. Journal of Geoph. Research 67(11), pp. 4375-4387.

Toth, J., 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geoph. Research 68(16), pp. 4795-4812.

Tricart, J., 1965, translated by C.J.K. de Jonge, 1972. The Landforms of the Humid Tropics, Forests and Savannahs. Longman Group Limited, London, 1972.

Umbgrove, J.H.F.,1929. De koraalriffen der Duizend eilanden (Java Zee). Wetensch. Meded. Dienst v.d. Mijnbouw, 12, 1929, Bandung.

Uyeda, S. & H. Kanamori, 1979. Back-arc opening and mode of subduction. J. Geophys. Res., 84, pp. 1049-1061.

Vail, P.R., J. Hardenbol & R.G. Todd, 1984. Jurassic unconformities, chronostratigraphy and sealevel changes from seismic stratigraphy and biostratigraphy. AAPG Memoir 36, pp. 129-144.

Vail, P.R., R.M. Mitchum & S. Thompson, 1977. Global cycles of relative changes of sea level. AAPG Memoir 26, pp. 83-97.

Van Beek, C.G.G., 1982. Een Geomorfologische bodemkundige studie van het Gunung Leuser nationale park, Noord Sumatra, Indonesië. Geographical Institute, University of Utrecht, The Netherlands, 135 pp.

Van Bemmelen, R.W., 1934. Geologische kaart van Java, blad 36, Bandung. Explanatory notes to sheet 36 (Bandung). Unpublished manuscript (in Dutch) at Geological Survey of Indonesia, Bandung.

Van Bemmelen, R.W., 1941. Geological map of Java, scale 1:100,000. Explanatory notes to sheets 73 (Semarang) and 74 (Oengaran). Unpublished manuscript (translated to English) at Geological Survey of Indonesia, Bandung.

Van Bemmelen, R.W., 1949. The geology of Indonesia. Netherlands government printing office, The Hague.

Van Den Beukel, J. & R. Wortel, 1986. Thermal modelling of arc-trench regions. Geol. en Mijnbouw No. 65, pp. 133-143.

Van der Linden, P., 1978. Contemporary soil erosion in the Sanggreman river basin related to the Quaternary landscape development; A pedogeomorphic and hydro-geomorphological case study in Middle-Java, Indonesia. Ph.D thesis, University of Amsterdam.

Van Elburg, H., G.B. Engelen & C.J. Hemker, 1987. FLOWNET, een computerprogramma voor de modellering van het net van stroomlijnen en equipotentiaallijnen, de weergave van de tijdstappen en animatie van het stromingsbeeld in een tweedimensionale verticale doorsnede van de ondergrond. User Manual. Institute for Earth Sciences, Free University, Amsterdam.

Van Genuchten, M.Th. & R.W.Cleary, in G.H. Bolt (ed.), 1981. Movement of solutes in soil: computer-simulated and laboratory results. pp. 349-383. In Soil Chemistry, B. Physico-chemical models. Developments in soil sciences 5B. Elsevier Scientific Publishing Company, Amsterdam, 1982.

Van Schaik, A., 1986. Colonial control and peasant resources in Java. Ph.D thesis, Instituut Sociale geografie, Universiteit van Amsterdam.

Van Zeist, W., 1983. The prospects of palynology for the study of prehistoric man in Southeast Asia. Mod. Quaternary Res. SE Asia, 8 (1983/1984), pp. 1-15.

Verheye, W., 1981. Bodemmilieu en Bodemvorming in Aride en Sub-Aride Zones. Rijks Universiteit Gent. Faculteit van de Wetenschappen Laboratorium voor Fysische Aardrijkskunde en Regionale Bodemkunde. Ph.D. thesis.

Verstappen, H.Th., 1960. Preliminary geomorphological results of the Star Mountains expedition 1959. Tijdschr. K. Ned. aardr. Gen., 77, pp. 305-311.

Verstappen, H.Th., (editors G.J. Bartstra & W.A. Casparie) 1974. On Paleoclimates and Landform Development in Malesia. Symposium on Modern Quaternary Research in Indonesia, Groningen May 16, 1974. Modern Quaternary Research in Southeast Asia. A.A. Balkema/Rotterdam, 1975.

Verstappen, H.Th., 1980. Quaternary climatic changes and natural environment in SE Asia. Geojournal 41, p45-54.

Walcott, R.I., 1972. Past sea levels, eustasy and deformation of the Earth. Quaternary Res., 2, pp. 1-14.

Weber, K.J., 1985. Delineation of the Reservoir by Identification of Environmental Types and Early Estimation of Reserves. Lecture notes, Department of Mining, University of Technology, Delft.

Wenzens, G., 1978. Zur Genese von Schwemmfachern und Pedimenten in den Basin and Range-Landschaften Nordamerikas. Z. Geomorph. N.F., Suppl. Bd 30, Berlin. Stuttgart, Oktober 1978, pp. 74-92.

White, B., 1974. Agricultural involution (a critical note). Agro-economic survey, Jakarta.

Wijckerheld Bisdom, M.A., 1988. Hydrogeological study shallow groundwater coastal lowlands, Tegal, Indonesia. Unpublished M.Sc. thesis, Faculty of Earth Sciences, Free University, Amsterdam.

Williams, M.A.J., 1975. Late Pleistocene tropical aridity synchronous in both hemispheres?. Nature, 253, pp. 617-618.

Williams, M.A.J., 1985. Pleistocene aridity in tropical Africa, Australia and Asia. In 'Environmental Change and Tropical Geomorphology' by Douglas, I. & spencer, T. (ed.). A publication of the British Geomorphological Research Group. Georg Allen & Unwin, London.

Wilson, J. Tuzo, 1963. Continental drift. In 'Continents adrift and Continents aground', with introductions by Wilson J.T., Scientific American, 1963-1976. Freeman W.H. and Company, San Fransisco.

Wirthmann, A., 1985. Offene Fragen der Tropengeomorphologie. Z. Geomorph. N.F., Suppl.-Bd. 56, Berlin, Stuttgart, November 1985, pp. 1-12.

Wortel, M.J.R., 1986. Dynamical aspects of active continental margins. Geologie en Mijnbouw 65: pp. 119-132 (1986).

Yaalon, D.H., (editor) 1981. Aridic Soils And Geomorphic Processes. Proceedings of the International Conference of the International Society of Soil Science. Jerusalem, Israel, March 29-April 4, 1981. Catena supplement 1.

Zimmerman, U., D. Ehhalt & K.O. Münnich, 1967. Soil-water movement and evapotranspiration: changes in isotopic composition of the water. Proc. Symp. Isotopes in Hydrology, Vienna, 1966. IAEA, Vienna, pp. 567-584.

Zuidam, R.A., 1976. Geomorphological development of the Zaragoza region , Spain; processes and land forms related to climatic changes in a large Mediterranean river basin.

GOVERNMENTAL PUBLICATIONS

Biro Pusat Statistik, Jakarta, Indonesia. Penduduk Indonesia 1985 menurut provinsi. Hasil pendaftaran rumahtangga (angka sementara). Seri Supas 85, No. 3, 1986.

Biro Pusat Statistik, Jakarta, Indonesia. Penduduk Jawa menurut propinsi dan kabupaten/kotamadya. Hasil pencacahan lengkap sensus penduduk 1980. Seri L No. 5, 1981.

Biro Pusat Statistik, Jakarta, Indonesia. Penduduk Jawa-Madura, hasil registrasi penduduk, 1971. 1973.

Biro Pusat Statistik, Jakarta, Indonesia. Sensus Pertanian Jawa Barat 1983.

Biro Pusat Statistik, Jakarta, Indonesia. Ulasan singkat hasil sensus penduduk 1980 (A brief note on the 1980 population sensus). 1982

Biro Pusat Statistik, Kabinet Menteri Pertama, Jakarta, Indonesia. Sensus penduduk 1961. Angka-angka sementara. Seri SP.-1, 1963.

Department of Communications, Indonesia, The Institute of Meteorology and Geophysics. Rainfall observations in Indonesia, monthly rainfall and number of rain days. Observation years 1970-1979.

Directorate of environmental geology (Ministry of mines and energy). Hydrogeological map of Indonesia, scale 1:2,500,000. Sheet Indonesia. Compiled by A. Djaeni et al. Explanatory note compiled by S. Puspowardoyo. In cooperation with the German Hydrogeological Advisory group (CTA-40), Technical cooperation project of the Federal Republic of Germany.

Directorate of environmental geology (Ministry of mines and energy). Hydrogeological map of Indonesia, scale 1:250,000. Sheet II : Cirebon (Java). Compiled by Soetrisno S. (1985). In cooperation with the German Hydrogeological Advisory group (CTA-40), Technical cooperation project of the Federal Republic of Germany.

Directorate of environmental geology (Ministry of mines and energy). Hydrogeological map of Indonesia, scale 1:250,000. Sheet VI : Pekalongan (Java). Compiled by A. Tabrani Effendi (1985). In cooperation with the German Hydrogeological Advisory group (CTA-40), Technical cooperation project of the Federal Republic of Germany.

Kantor Statistik, propinsi Jawa Tengah, Semarang. Luas Penggunaan tanah di Jawa Tengah, Keadaan akhir 1985. Laporan 33521.8605, Semarang 1986.

National Urban Development Strategy Project, 1985. Projected urban population year 1985.

National Urban Development Strategy Project, 1985. Projected urban population year 2000.

National Urban Development Strategy Project, 1985. Urban growth and structure in Indonesia.

Regional Development Planning Project, West Java. LTA-47, 1986. Second Technical Report.

Regional Development Project West Java LTA-47, 1986.